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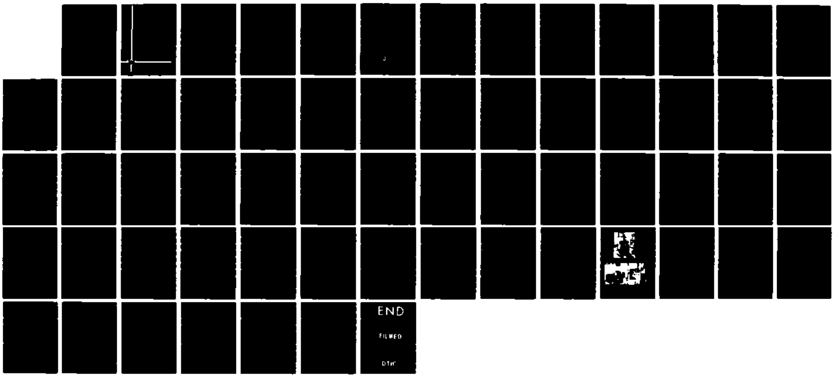

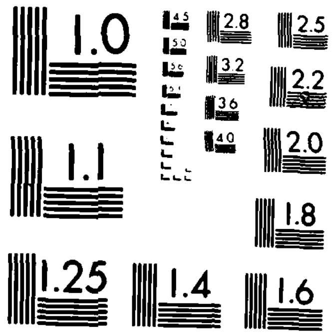


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NATIONAL BUREAU OF STANDARDS 1963 A

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This report supersedes Report No. 2409 which was previously printed.

**Report 2409**



# EVALUATION OF THE $L_{10}$ LIFE OF MILITARY GREASES IN WHEEL BEARINGS BY COMPUTER ANALYSIS

**May 1984**



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Belvoir Research & Development Center
Fort Belvoir, Virginia 22060

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Endurance test method
Newton-Raphson method

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of the wear life study was to develop a methodology that would be capable of predicting performance of military grease under laboratory environment. The desired methodology can be used to reduce the current maintenance costs and to improve future systems. In the initial study, the maximum likelihood (ML) computer program for the two-parameter Weibull probability distribution has been developed on the failure data of grease. The results show that this computer program can reliably predict $L_{10}$ life which can also be denoted as the minimum life of greases.

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# EVALUATION OF THE $L_{10}$ LIFE OF MILITARY GREASES IN WHEEL BEARINGS BY COMPUTER ANALYSIS

## I. INTRODUCTION

The research and development of fuel and lubricant products involves a sequence of events starting with laboratory investigations and testing followed by component evaluation and engine dynamometer testing and ending with field and fleet user-testing to certify the performance of the products in question. This sequence of basic research, exploratory development, and advanced development is the established mechanism needed to provide the basis for development of the final procurement specification for a new lubricant, fluid, or grease. One of the major concerns in the execution of these research efforts is the time requirement in testing and evaluation and the comprehensive test methodologies which can be utilized to predict performance life of the product in question. Many product specifications incorporate functional-type testing procedures as well as specifying chemical/physical property requirements. However, these testing procedures (i.e., anti-wear performance using a Four-Ball Wear Tester, engine dynamometer tests for determining deposit tendencies, etc.) generally define an established level of performance and do not provide a means for projecting "performance life."[1]

Because of the inherent uncertainty of the performance tests, a long endurance testing time, and the high cost incurred by the fleet testing, a project was initiated to develop a methodology that would be capable of predicting performance (i.e., system durability, overhaul intervals, mean-time-between-failure, etc.) within certain levels of confidence. This methodology would be used in certain laboratory-type performance tests and to process the obtained data to project wear life and/or probability of system component failure.

Some work has been done along these lines with roller-bearing systems where the $B_{10}$ life value, the 90 percent reliable bearing life called $L_{10}$ life, has been projected. A recent SAE paper illustrated this approach in predicting Weibull failure profiles for the hydraulic pump and engines operating on synthetic fuels.[2] [3] In a similar approach, the desired end results of this methodology can be used to predict the $L_{10}$ life which could be denoted as the minimum life of greases, hydraulic fluids, lubricants, and engine oils. Eventually, this methodology could be used to improve future systems while significantly reducing maintenance costs.

---

1 Military Specification MIL-H-46170, "Hydraulic Fluid, Rust Inhibited, Fire Resistant, Synthetic Hydrocarbon Base," 18 August 1982

2 R. Bertodo, Extenders and Diluents, SAE paper 800831, June 1980.

3 C. H. Medlin and F. L. Elsaesser, Weibull/Weibayes Analysis of Hydraulic Pump Malfunction Data, SAE Paper 831542, October 1983.

Initially, this project has been divided into the following three phases:

Phase I—Develop the mathematical modeling system to evaluate functional fluid performance of grease products.

Phase II—Select or develop accelerated endurance testing method(s).

Phase III—Modify Phase I or Phase II to correlate to field performance if necessary.

In Phase I, a mathematical modeling system was developed which can be used for a variety of systems (i.e., failure criteria or probability of failure with input provided by laboratory tests, system tests, and field data). Phase II will select and develop the accelerated endurance test method(s) which are hoped to result in good repeatability and reproducibility while being of short duration. At the same time, a matrix of potential test parameters related to the field conditions will be defined for the one product class of greases. (Note: this will be expanded later into fluids and automotive engine oils.) Then, the predictive life data will be generated under controlled laboratory conditions. Finally, the desired $L_{10}$ life of the materials tested will be compared to their field performance in the final Phase (III).

Since the wear life project was initiated, the maximum likelihood ML computer program for the two-parameter Weibull probability distribution has been developed to meet the primary objective of Phase I using the HP 9830A computer and HP 9862A calculator plotter. This method was applied to the conventional Military Specification MIL-G-10924C, "Grease, Automotive and Artillery (GAA)," commercial grease and candidate improved greases considered in the course of the project for developing and a long-life military grease.[4]

Finally, this report identifies the tested greases using their specification designations. Also, it describes the ML computer program and illustrates how the $L_{10}$ military grease life was determined for this investigation.

## II. THE MAXIMUM LIKELIHOOD (ML) COMPUTER PROGRAM FOR THE TWO-PARAMETER WEIBULL DISTRIBUTION AND THE EXTREME VALUE DISTRIBUTION

The Weibull probability distribution was initially developed by Waloddi Weibull, Professor of Applied Physics at Royal Institute of Technology in Stockholm, Sweden. The primary motivation in developing this distribution was the study of the strength and fatigue life of materials. After the Weibull distribution had been accepted for studies on the fatigue of

4 Military Specification MIL-G-10924C, "Grease, Automotive and Artillery (GAA)," 5 February 1971.

materials, it was widely applied in the field of reliability, fatigue testing, and quality control.[5] In an earlier study, the $L_{10}$ fatigue lives of rolling bearings were computed using the AFBMA-ASA standards.[6] This methodology uses the two-parameter Weibull probability distribution. The distribution equation is described as follows:[7]

$$F(X) = 1 - e^{-(X/\theta)^{\beta}} X \geq 0,$$

where F(X) represents the probability of bearing fatigue life. The function F(X) is called the cumulative distribution for a random variable X, such as bearing fatigue. The terms $\beta$ and $\theta$ refer to the shape and scale parameters, respectively. Unfortunately, these parameters usually are not known. The best method for the estimation of these parameters is an ML method, which gives a solution using simultaneous equations.[8] Generally, these unknown parameters are determined from the ML equation of extreme value distribution. Their relationship is expressed by the following mathematical form:

$X = \mathrm{Exp}\,(Y)$, $\theta = \mathrm{Exp}\,(\lambda)$, and $\beta = 1/\delta$, where X, Y are random variables for Weibull and extreme value distribution. $\lambda$, $\delta$ are the parameters of extreme value distribution. This extreme value distribution often applies to corrosion studies, the prediction of life, and the measurement of metal strength. The ML equation and the two partial differential equations of extreme value distribution are described in the following form:

ML equation:

$$\mathrm{MAX}\ L = \sum_i{}' [-\ln(\delta) - \exp[(y_i - \lambda)/\delta] + [(y_i - \lambda)/\delta] - \sum_i{}'' \exp[(y_i - \lambda)/\delta]. \quad (1)$$

Constraining partial differential equations:

$$\partial L/\partial\lambda = (1/\delta)(\sum_i \exp[(y_i - \lambda)/\delta] - r] = 0; \text{ and} \quad (2)$$

$$\partial L/\partial\delta = (1/\delta)\,(\sum_i [(y_i - \lambda)/\delta]\exp[(y_i - \lambda)/\delta] - r] = 0, \quad (3)$$

$$i = 1, 2, 3 \ldots$$

---

[5] Fred H. Steiger, "Practical Applications of the Weibull Distribution Function," Chem. Tech. April 1971.

[6] T. A. Harris, "Load-Life Characteristics of Rolling Bearings," standard handbook of lubrication engineering, 1968.

[7] K. C. Kapur and L. R. Lamberson, "Reliability in Engineering Design," 1977.

[8] Wayne Nelson, "Applied Life Performance and Data Analysis," Wiley series in probability and mathematical series.

where $\Sigma$ = sum of failure and unfailure data;

$\Sigma'$ = sum of failure data;

$\Sigma''$ = sum of unfailure data; and

r = the number of failures in a sample.

From the above equations, the ML estimators ($\lambda$, $\delta$) must be satisfied in the two constraining equations (2) and (3). Concurrently, these ML estimators ($\lambda$, $\delta$) establish the ML equation (1) and can be used to calculate a numerical maximum value. Finally, these values ($\lambda$, $\delta$) are converted to the Weibull parameters ($\theta$, $\beta$) using their relationship. One problem area is that the above constraining equations (2) and (3) are not linear. Therefore, these equations must be iteratively solved by the computer. The best iterative method is the well-known Newton-Raphson method which gives quicker convergence. The Newton-Raphson iterative equation is shown in the following form:[9]

$$\begin{pmatrix}\lambda\\ \delta\end{pmatrix}^{i+1} = \begin{pmatrix}\lambda_i\\ \delta_i\end{pmatrix} - \begin{bmatrix}-\partial^2L/\partial\lambda^2 & -\partial^2L/\partial\lambda\partial\delta\\ -\partial^2L/\partial\delta\partial\lambda & -\partial^2L/\partial\delta^2\end{bmatrix}^{-1}\begin{bmatrix}\partial L/\partial\lambda\\ \partial L/\partial\delta\end{bmatrix} \tag{4}$$

In practice, the Newton-Raphson method can be effective in providing the ML estimators ($\lambda$,$\delta$), when the initial estimates ($\lambda_i$, $\delta_i$) are sufficiently close to the optimum value ($\lambda$, $\delta$). However, for poor initial estimates ($\lambda_i$, $\delta_i$), the procedure often fails to result in convergence.

The major advantages of the ML method are good estimates of the Weibull parameters, reduced computational time, and good repeatability. This method, also, provides the covariance matrices and the confidence limit for distribution percentiles. On the other hand, this method requires a special computer program for the computations. The ML computer program for both Weibull and extreme value distribution has been developed using the above equations ((1) through (4)). This computer program was written in the basic computer language and consists of a main program, subroutine program, and Weibull plotting routine. This plotting routine uses $X = \ln(\ln(1/(1 - F(X))$ and $Y = \ln t$ to construct the plot.[10] The ML computer program is given in Appendix A.

## III. THE $L_{10}$ LIFE OF MILITARY GREASES AND THE COMMERCIAL GREASE

The $L_{10}$ life, once developed, can fulfill an important role in military greases research and development. It can be used to obtain the proper relubrication interval of military vehicles. In the development of long-life military grease, moreover, the candidate greases can be differentiated by their $L_{10}$ life determined in the laboratory or field. This approach has already been

[9] M. J. D. Powell, "A Survey of Numerical Methods for Unconstrained Optimization," in *Perspectives on Optimization*, A. M. Geoffrion, Editor, Addison-Wesley.

[10] K. C. Kapur and L. R. Lamberson, "Reliability in Engineering Design," 1977.

applied to the bearing fatigue life (rating life). Most bearing manufacturers widely accept the $L_{10}$ life of bearing as a design criterion.[11] With wear life projections, the $L_{10}$ life of military greases can be predicted using the ML computer program, two-parameter Weibull probability distribution, and the failure data. The failure data were collected from two previous SKF contracts and the current SKF contract.[12] [13] These laboratory data were obtained using an industrial test method with a higher than standard temperature (121° C) in the SKF R-2 Endurance Test Machine. This industrial method and the test machine used to obtain the data are described in detail in Appendix B. Initially, the following 10 military greases and 1 commercial grease were evaluated:

| CODE | TYPE | SPECIFICATION |
|---|---|---|
| A | Grease, Automotive and Artillery (GAA) | MIL-G-10924C |
| B | GAA | MIL-G-10924C |
| C | Commercial product | |
| D | Grease, Aircraft General Purpose, Wide Temperature Range | MIL-G-81322B, AM3[14] |
| E | Grease, General Purpose | MIL-G-23549A/ASG[15] |
| F | Grease, Automotive and Artillery | MIL-G-10924D[16] |
| G | Grease, Multipurpose, Quiet Service (NAVY) | MIL-G-24139[17] |
| H | Grease, Molybdenum Disulfide, for Low and High Temperatures (NAVY) | MIL-G-21164C[18] |
| I | Candidate grease for improved GAA | Experimental Formulation |
| J | Candidate grease for improved GAA | Experimental Formulation |
| K | Candidate grease for improved GAA | Experimental Formulation |

---

11 T. A. Harris, "Load-Life Characteristics of Rolling Bearings," standard handbook of lubrication engineering, 1968.

12 Contract No. DAAK 70-77-C-0034, "Performance of Automotive Wheel Bearing Greases," Final Report, SKF Inc.

13 Contract No. DAAK 70-79-C-0213, "Performance Evaluation of Automotive Wheel Bearing Greases," Final Report, SKF Inc.

14 Military Specification MIL-G-81322 B, AM3, "Grease, Aircraft General Purpose, Wide Temperature Range," 24 September 1975.

15 Military Specification MIL-G-23549A/ASG, "Grease, General Purpose," 17 September 1976.

16 Military Specification MIL-G-10924D, "Grease, Automotive and Artillery," 13 June 1983.

17 Military Specification MIL-G-24139, "Grease, Multipurpose, Quiet Service," 25 April 1966.

18 Military Specification MIL-G-21164C, "Grease, Molybdenum Disulfide, for Low and High Temperatures," 17 July 1968.

Figure 1 shows the probability life diagram obtained for military grease. This diagram was constructed to X and Y axes representing the cumulative probability in percent and hours-to-failure, respectively. The $L_{10}$ life of greases tested are summarized in Table 1, which includes the lower control limit (LCL), median $L_{10}$ value (MED), and upper control limit (UCL) of the 90 percent confidence intervals. The physical and chemical properties of greases A to M are shown in Table 2. Obviously, the grease E (MIL-G-23549A/ASG, General Purpose) shows the best overall performance among the greases tested under laboratory environment. The projected $L_{10}$ life is approximately equivalent to 20,912 mi, which presents a longer life than theoretical fatigue bearing life (15,608 mi). The conventional wheel bearing grease (MIL-G-10924C) has marked only 2,298 mi. This $L_{10}$ value is approximately 9 times less than the grease E (MIL-G-23549A/ASG) and 7 times less than the theoretical fatigue bearing life. This implies that the bearing will have to be relubricated at a greater frequency in order to avoid bearing damage. Throughout our observation, the $L_{10}$ life seemed to be dependent upon the thermal effectiveness and load characteristic of each grease. Evidently, Figure 2 indicates the thermal effectiveness on the $L_{10}$ life (MIL-G-10924C) which was determined at two different temperatures, usually at 121° C and 30° C. In fact, their $L_{10}$ life difference is approximately 203 h (13,540 mi). The individual grease lives, with 90 percent confidence intervals, are shown in Figures 3 to 14 and their numerical percentile lives are provided in Tables 3 to 14.

## IV. DISCUSSION AND CONCLUSIONS

In wear life studies, the ML computer program which was developed for the two-parameter Weibull probability distribution, can be used for predicting performance of greases as well as fatigue life of bearings. Evidently, the test results indicate that the grease failure data used in this evaluation, follow the Weibull distribution. This computer program met our initial objective to develop mathematical modeling systems which have the ability to project wear life and/or probability of failure using input data provided by laboratory tests and field data.

From the laboratory results, the $L_{10}$ life of military greases tested at 121° C varied from about 27 h to 313 h. Their ranking is as follows:

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ranking* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Grease | E | J | D | I | K | G | F | C | A | B | H. |

*Number 1 had the longest $L_{10}$ life, representing the best grease.

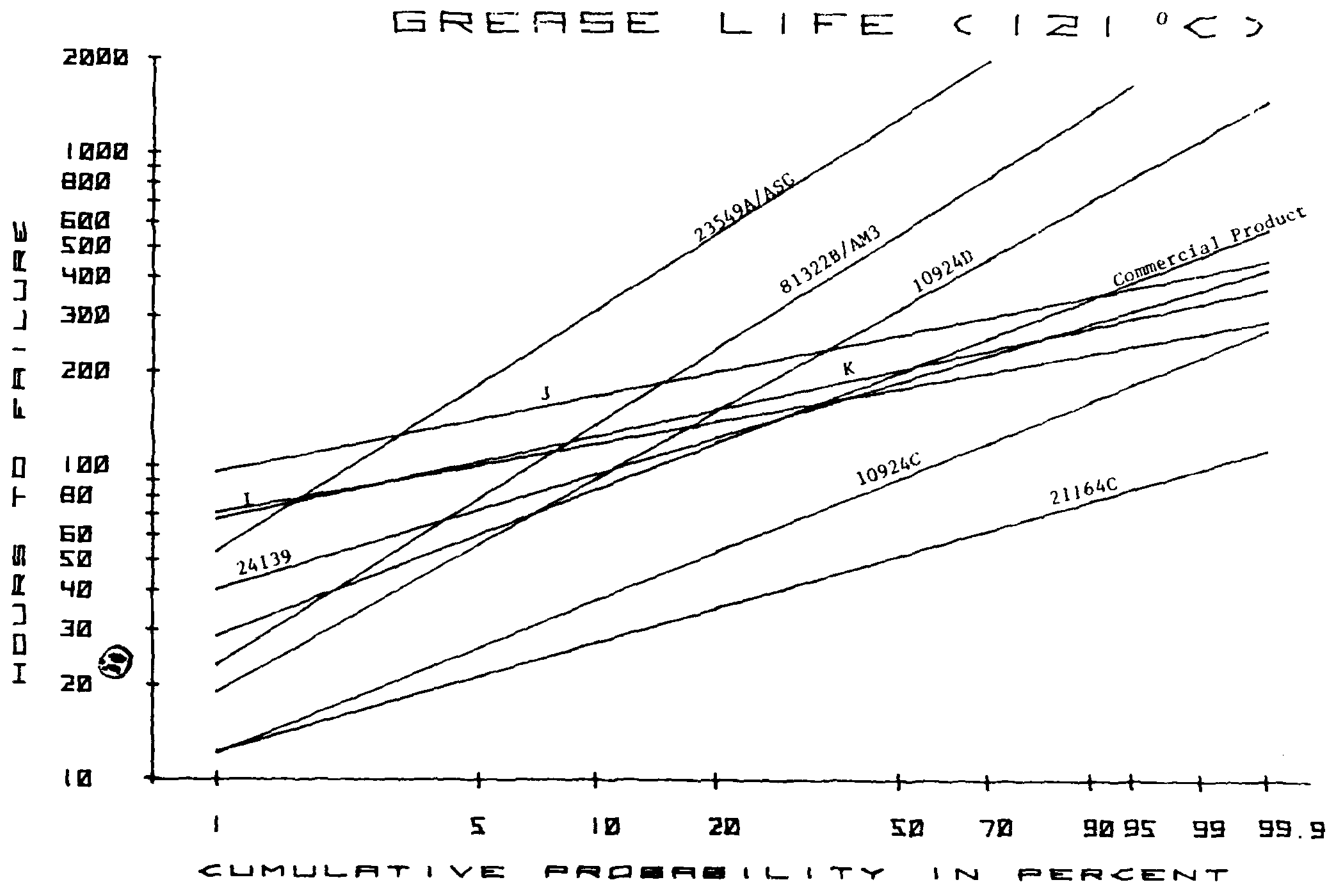


Figure 1. Military greases (121° C).

Table 1. The $L_{10}$ Life of Military and Commercial Greases

| Grease Code | Specification No. | LCL (h) | MED (h) | UCL (h) |
|---|---|---|---|---|
| A | MIL-G-10924C | 25 | 37 | 56 |
| B | MIL-G-10924C | 17 | 31 | 55 |
| C | Commercial Product | 55 | 84 | 127 |
| D | MIL-G-81322B, AM3 | 64 | 135 | 285 |
| E | MIL-G-23549A/ASG | 130 | 313 | 755 |
| F | MIL-G-10924D(P) | 47 | 90 | 174 |
| G | MIL-G-24139 | 68 | 94 | 129 |
| H | MIL-G-21164C | 15 | 27 | 47 |
| I | Experimental Formulation | 92 | 125 | 168 |
| J | Experimental Formulation | 120 | 168 | 233 |
| K | Experimental Formulation | 91 | 118 | 152 |
| A* | MIL-G-10924C | 189 | 240 | 305 |

Notes:

1. **The Laboratory Endurance Test Conditions.**

   a. Test Bearing Specimens:

      Outboard: LM12749/LM12710

      Inboard: LM68149/L68110

   b. Operation Temperature: 121° C

   c. Loads:

      Radial: 8.34KN(1,875 ft-lb)

      Thrust: 2.49KN(560 ft-lb)

   d. Speed: 800 r/min (65 mi/h)

   e. Maximum Operation Times: 300 h

2. **Proposed A*:** This grease tested at 30° C.

Table 2. The Physical and Chemical Properties of Tested Military Greases

| TEST | ASTM METHOD | GREASE | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F | G | H |
| Penetration 60 Double Strokes | D217 | 283 | 281 | 285 | 315 | 312 | 298 | 295 | 285 |
| Dropping Point, °C | D2265 | 144 | 143 | 260+ | 260+ | 260+ | 144 | 232 | 185 |
| Oil Separation, % | D1747 | 6.0 | 5.2 | 3.0 | 3.1 | 2.9 | 2.4 | 0.5 | 3.2 |
| Evaporation, % | D972 | 5.8 | 5.3 | 2.8 | 0.2 | 2.8 | 1.2 | 1.3 | 1.7 |
| 4 Ball Extreme Pressure Load Wear Index | D2596 | 35.6 | 32.1 | 40.0 | 40.5 | 92.0 | 37.9 | 64 | 57 |
| 4 Ball Wear, Scar Diameter, mm | D2266 | 0.53 | 0.55 | 0.40 | 0.45 | 0.49 | 0.47 | — | — |
| Base Oil Viscosity 100° C cs | | 13.3 | 13.3 | 129.3 | 29.3 | 330.7 | 38.4 | 36.5 | 9.7 |
| Base Oil Type | | N | N | P | SH | P | N | H | D |
| Thickener Type | | Ca | Ca | Li | clay | Li | Ca | clay | Li/MOS2 |

Notes:

N: Naphthenic

Ca: Calcium

$MOS_2$: Molyb. Disulfide

P: Paraffinic

Li: Lithium

SH: Synthetic Hydrocarbon

clay: Bentonite Clay

H: Hydrocarbon


**Figure 2. Life of product A at two different temperatures (121° C, 30° C) MIL-G-10924C.**

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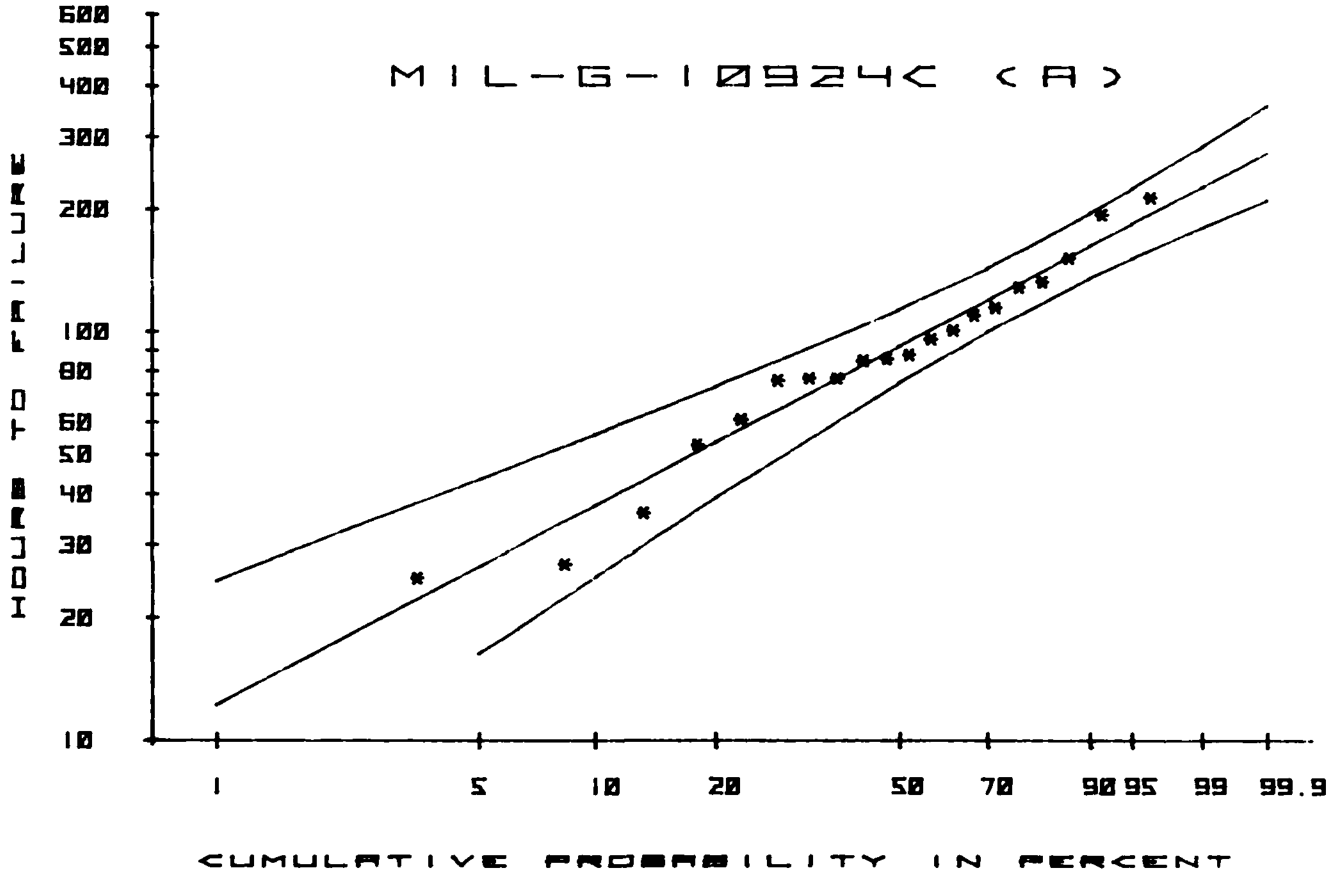


Figure 3. Life of product A, MIL-G-10924C.

TABLE 3.LIFE OF PRODUCT A,MIL-G 10924

F(X)=1-EXP(-(X/A)↑B)

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE(BETA) PARAMETER= 2.1023
LOWER LIMIT= 1.5863
UPPER LIMIT= 2.7860

SCALE PARAMETER= 109.4419
LOWER LIMIT= 90.9827
UPPER LIMIT= 131.6463

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 151.0372 | 1.4197 |
| SHAPE | 1.4197 | 0.1295 |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 12.2706 | 6.1070 | 24.6550 |
| 5.0000 | 26.6433 | 16.3308 | 43.4680 |
| 10.0000 | 37.5227 | 25.1291 | 56.0286 |
| 20.0000 | 53.6192 | 39.1872 | 73.3662 |
| 50.0000 | 91.9323 | 74.8322 | 112.9400 |
| 70.0000 | 119.5450 | 100.0218 | 142.8789 |
| 90.0000 | 162.7353 | 135.5703 | 195.3435 |
| 95.0000 | 184.4359 | 151.6559 | 224.3013 |
| 99.0000 | 226.2950 | 180.2670 | 284.0753 |
| 99.9000 | 274.4337 | 210.4616 | 357.8509 |

L10

| LCL | MED | UCL |
|---|---|---|
| 25.1291 | 37.5227 | 56.0286 |

L50

| LCL | MED | UCL |
|---|---|---|
| 74.8322 | 91.9323 | 112.9400 |

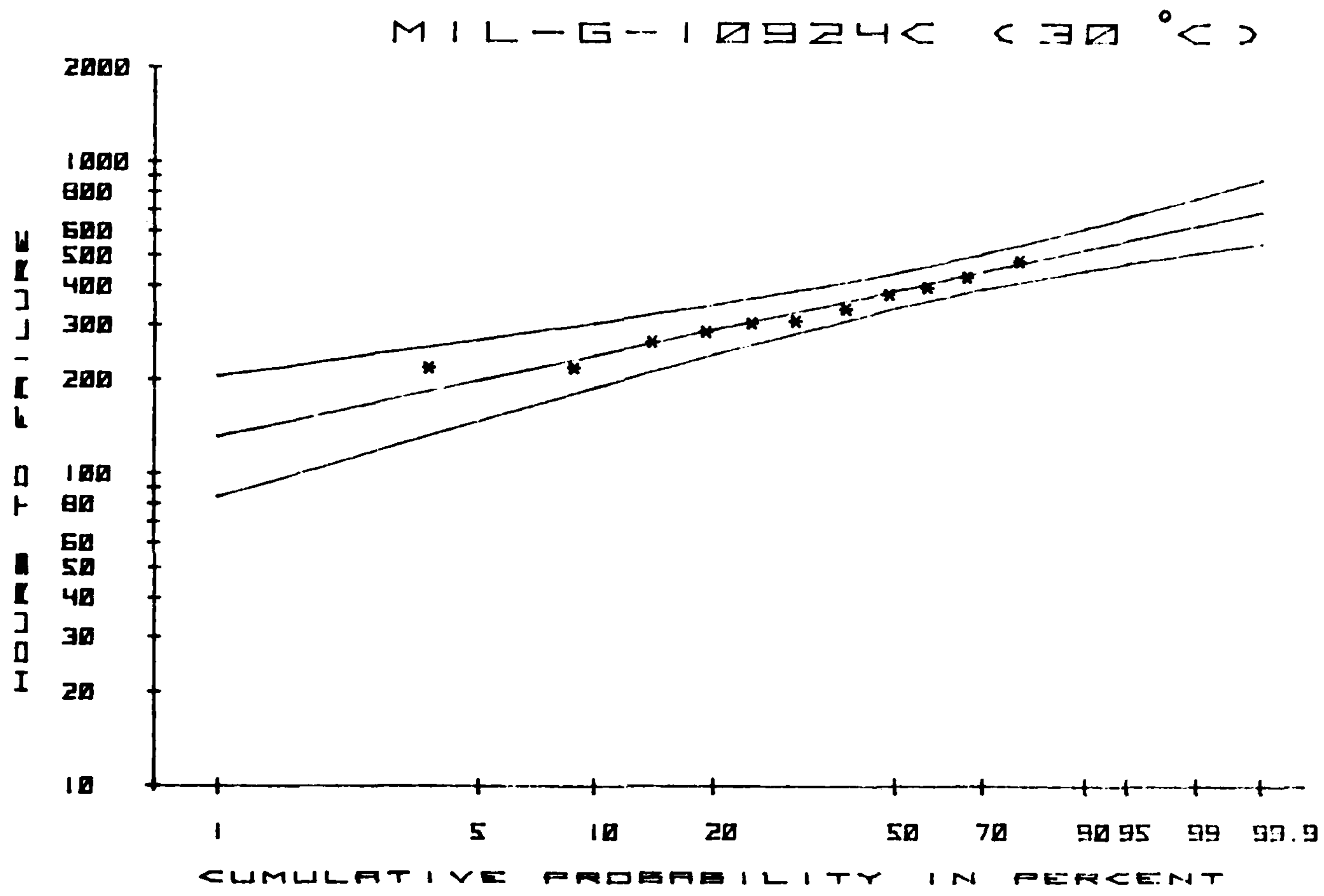


Figure 4. Life of product A (30° C), MIL-G-10924C.

## Table 4. Life of Product A, (30° C), MIL-G-10924C

```
F(X)=1-EXP(-(X/A)↑B)

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE(BETA) PARAMETER= 3.9176
LOWER LIMIT= 2.6948
UPPER LIMIT= 5.6952

SCALE PARAMETER= 427.3942
LOWER LIMIT= 376.3303
UPPER LIMIT= 485.3870
```

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 1092.8742 | -2.8147 |
| SHAPE | -2.8147 | 0.7939 |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 132.0902 | 84.6000 | 206.2392 |
| 5.0000 | 200.2453 | 148.4056 | 270.1931 |
| 10.0000 | 240.6357 | 189.4674 | 305.6227 |
| 20.0000 | 291.4406 | 242.8767 | 349.7150 |
| 50.0000 | 389.2227 | 342.2189 | 442.6825 |
| 70.0000 | 446.1327 | 393.4499 | 510.4155 |
| 90.0000 | 528.7944 | 452.2190 | 618.3364 |
| 95.0000 | 565.5350 | 475.9838 | 671.9343 |
| 99.0000 | 631.1418 | 515.4418 | 772.8126 |
| 99.9000 | 699.9637 | 553.9371 | 884.4851 |

L10

| LCL | MED | UCL |
|---|---|---|
| 189.4674 | 240.6357 | 305.6227 |

L50

| LCL | MED | UCL |
|---|---|---|
| 342.2189 | 389.2227 | 442.6825 |

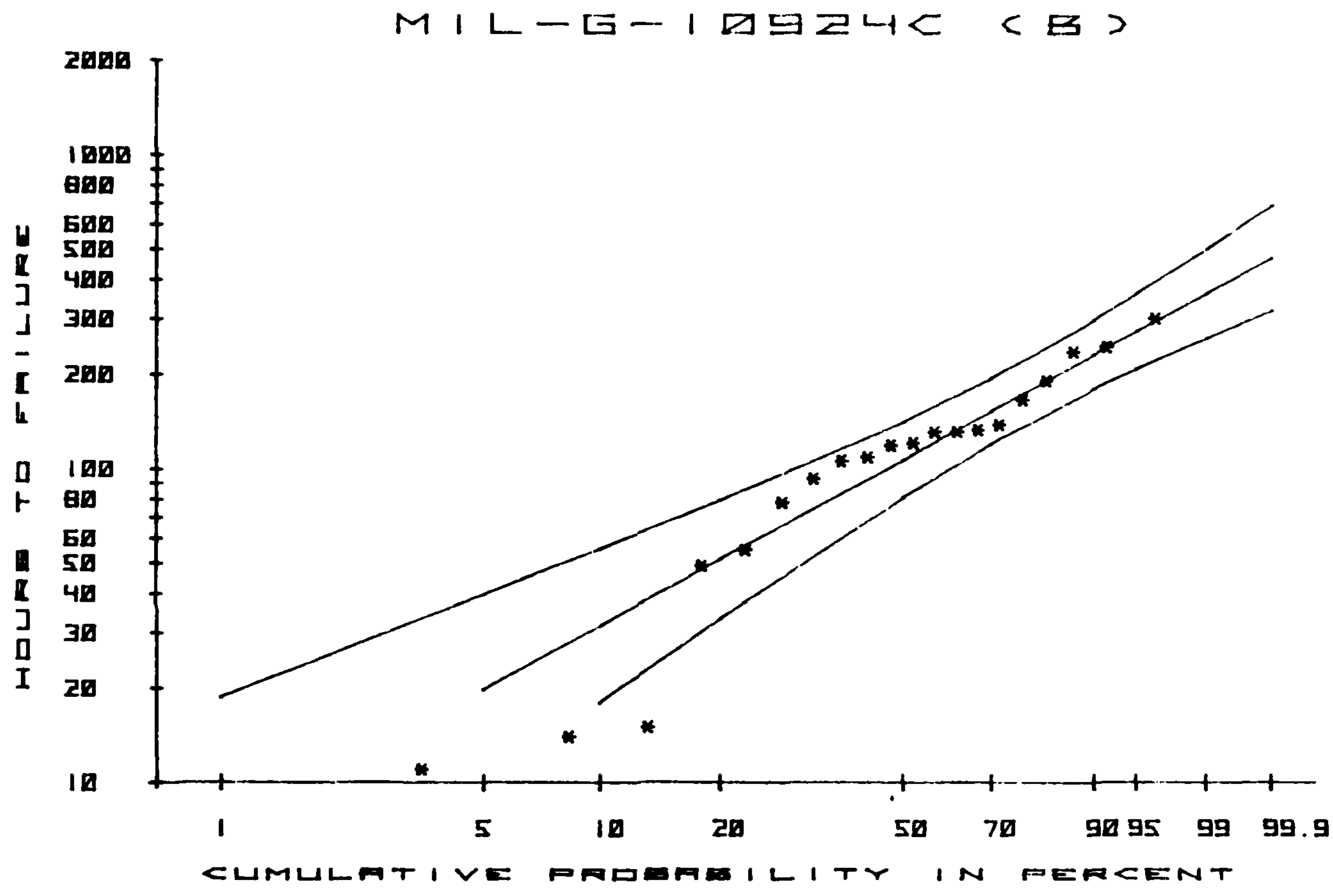


Figure 5. Life of product B, MIL-G-10924C.

TABLE 5.LIFE OF PRODUCT B:MIL G-10924

F(X)=1-EXP(-(X/A)^B)

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE(BETA) PARAMETER= 1.5500
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UPPER LIMIT= 2.0943

SCALE PARAMETER= 134.7[illegible]
LOWER LIMIT= 105.1585
UPPER LIMIT= 172.7830

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 413.9144 | 1.7054 |
| SHAPE | 1.7054 | 0.0804 |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 6.9301 | 2.5613 | 18.7505 |
| 5.0000 | 19.8355 | 9.9284 | 39.6283 |
| 10.0000 | 31.5598 | 17.9768 | 55.4057 |
| 20.0000 | 51.2152 | 33.1495 | 79.1261 |
| 50.0000 | 106.4089 | 80.6017 | 140.4792 |
| 70.0000 | 151.9442 | 119.5102 | 193.1806 |
| 90.0000 | 230.8679 | 179.2275 | 297.3873 |
| 95.0000 | 273.5888 | 207.7561 | 360.2822 |
| 99.0000 | 361.0598 | 260.6987 | 500.0569 |
| 99.9000 | 469.0163 | 319.4812 | 688.5424 |

L10

| LCL | MED | UCL |
|---|---|---|
| 17.9768 | 31.5598 | 55.4057 |

L50

| LCL | MED | UCL |
|---|---|---|
| 80.6017 | 106.4089 | 140.4792 |

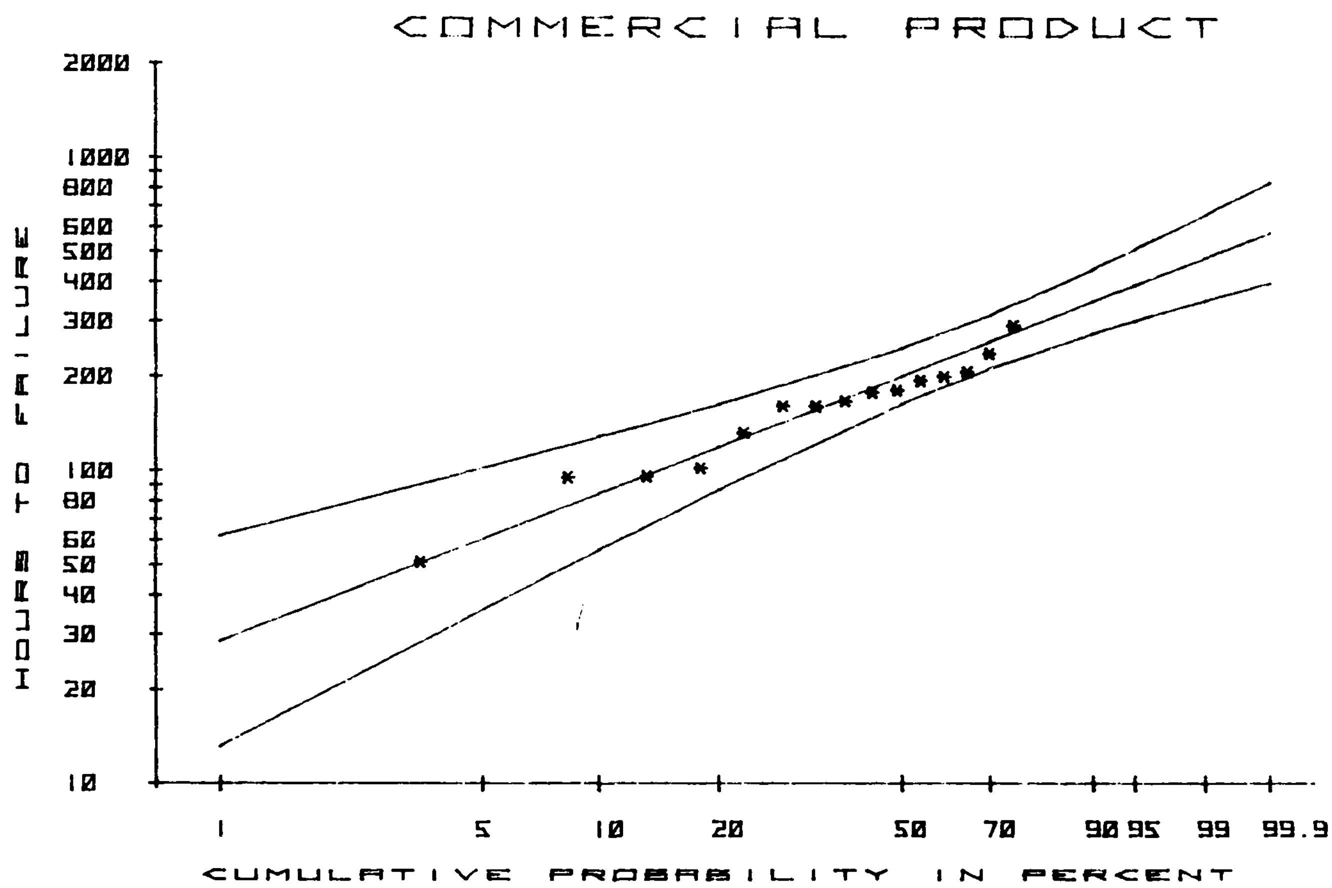



**Figure 6. Life of product C, Commercial product.**

TABLE 6. LIFE OF PRODUCT (COMMERCIAL PRODUCT)

F(X)=1-EXP(-(X/A)^B)

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE(BETA) PARAMETER= 2.1763
LOWER LIMIT= 1.5293
UPPER LIMIT= 3.0972

SCALE PARAMETER= 236.9003
LOWER LIMIT= 194.9420
UPPER LIMIT= 287.8894

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 788.1128 | 0.1660 |
| SHAPE | 0.1660 | 0.2179 |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 23.6148 | 13.2018 | 62.0275 |
| 5.0000 | 60.5137 | 35.4015 | 101.9987 |
| 10.0000 | 84.2359 | 55.5628 | 127.7058 |
| 20.0000 | 118.9180 | 86.8866 | 162.7580 |
| 50.0000 | 200.1828 | 163.1439 | 245.6308 |
| 70.0000 | 257.9931 | 211.8988 | 314.1143 |
| 90.0000 | 347.5358 | 274.5688 | 439.8938 |
| 95.0000 | 392.2051 | 301.7958 | 509.6985 |
| 99.0000 | 477.8805 | 349.4658 | 653.4827 |
| 99.9000 | 571.7464 | 399.0100 | 830.7660 |

L10

| LCL | MED | UCL |
|---|---|---|
| 55.5628 | 84.2359 | 127.7058 |

L50

| LCL | MED | UCL |
|---|---|---|
| 163.1439 | 200.1828 | 245.6308 |

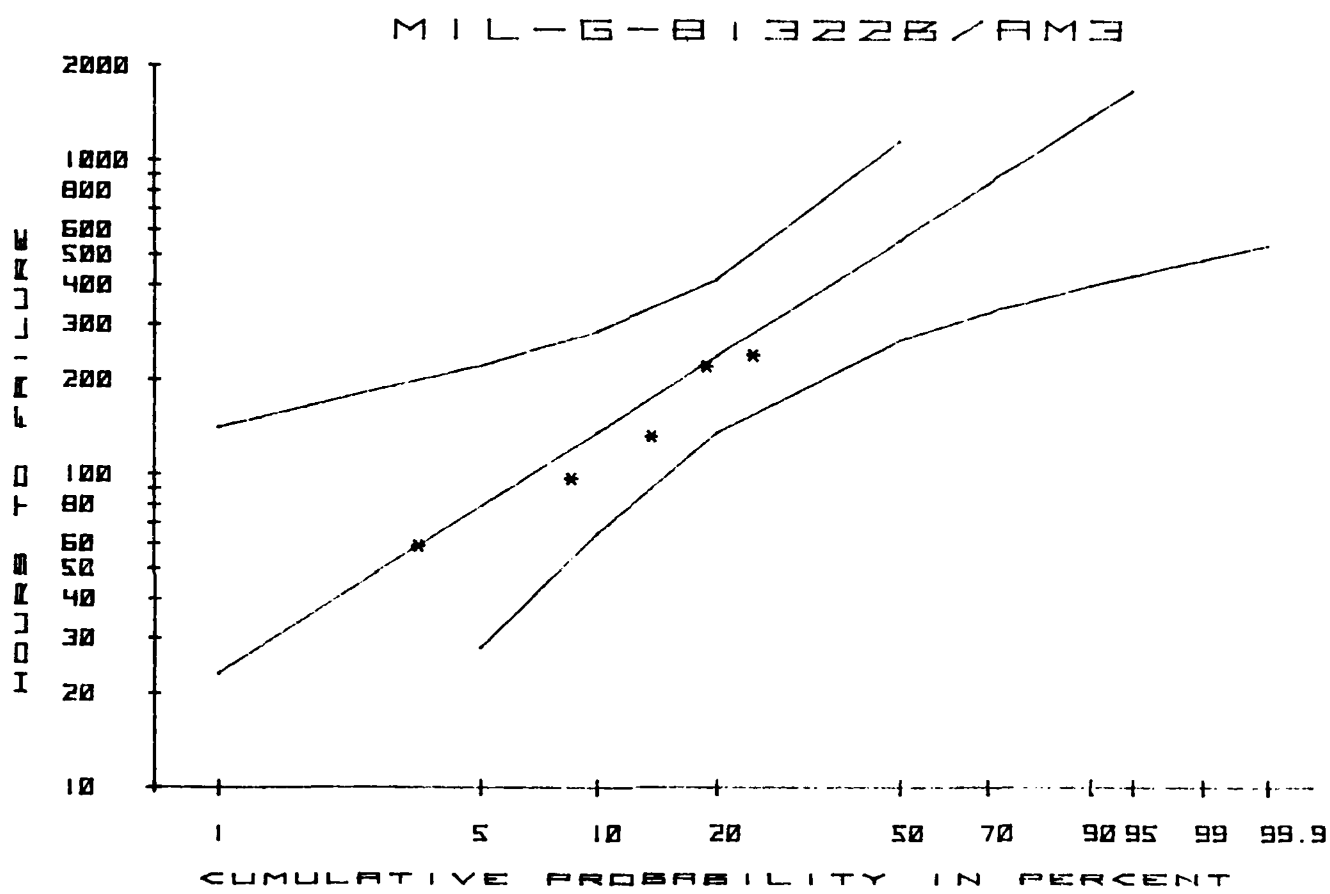



**Figure 7. Life of product D, MIL-G-81322B, AM3.**

TABLE 7.LIFE OF PRODUCT D,MIL-L-81322B,HNJ

F(X)=1-EXP(-(X/A)↑B)

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE(BETA) PARAMETER= 1.3335
LOWER LIMIT= 0.6681
UPPER LIMIT= 2.6615

SCALE PARAMETER= 731.5485
LOWER LIMIT= 308.2864
UPPER LIMIT= 1735.9285

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 147678.3416 | -165.6838 |
| SHAPE | -165.6838 | 0.3139 |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 23.2289 | 3.8183 | 141.3141 |
| 5.0000 | 78.8652 | 28.0440 | 221.7843 |
| 10.0000 | 135.3084 | 64.2013 | 285.1714 |
| 20.0000 | 237.5364 | 135.2587 | 417.1529 |
| 50.0000 | 555.7432 | 268.3213 | 1151.0472 |
| 70.0000 | 840.8133 | 328.3849 | 2152.8605 |
| 90.0000 | 1367.3437 | 400.3772 | 4669.6690 |
| 95.0000 | 1665.6533 | 431.1745 | 6434.5201 |
| 99.0000 | 2299.4693 | 484.3829 | 10916.0725 |
| 99.9000 | 3116.6129 | 538.5314 | 18036.6021 |

L10

| LCL | MED | UCL |
|---|---|---|
| 64.2013 | 135.3084 | 285.1714 |

L50

| LCL | MED | UCL |
|---|---|---|
| 268.3213 | 555.7432 | 1151.0472 |

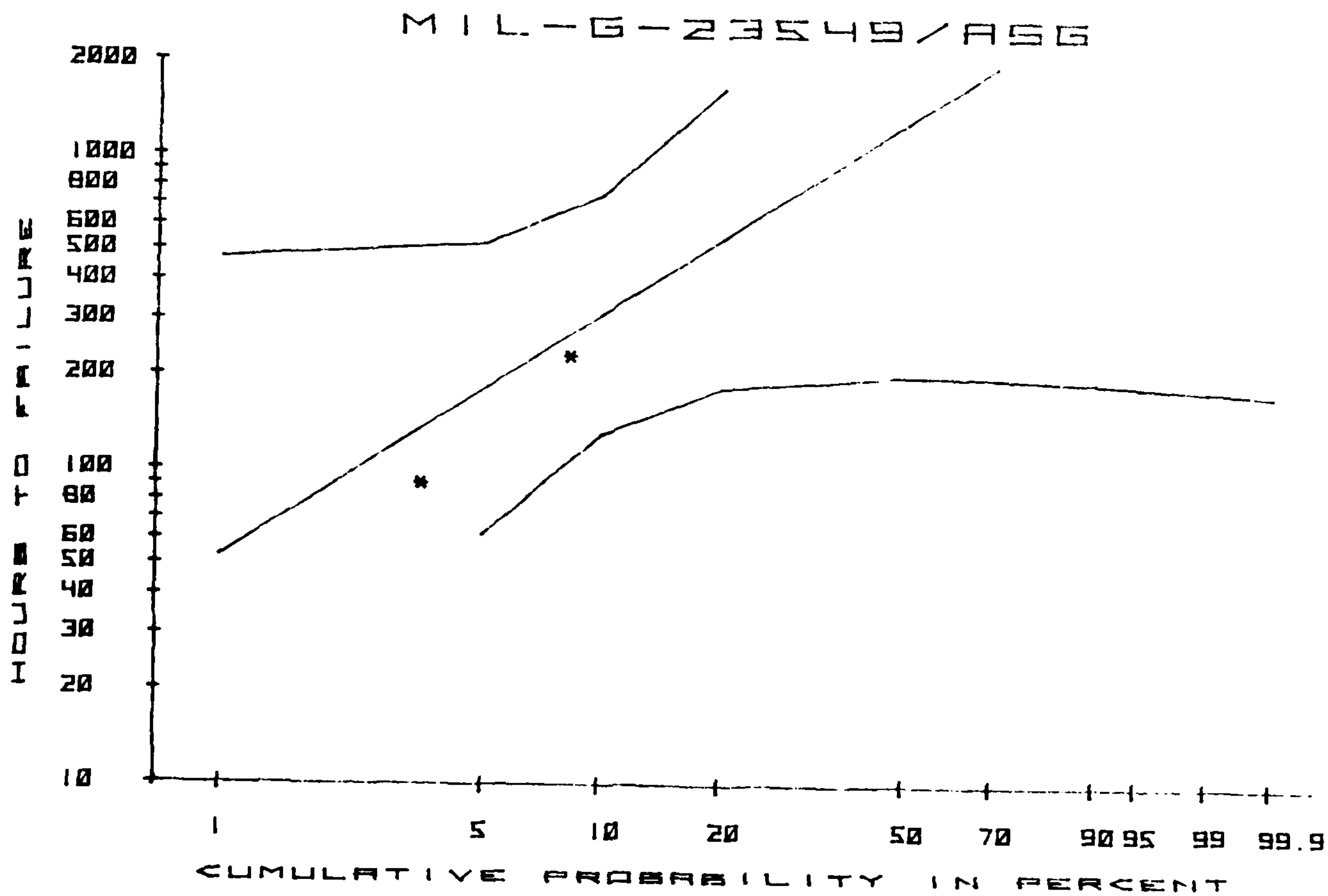



Figure 8. Life of product E, MIL-G-23549A/ASG.

TABLE 5. LIFE OF PRODUCT [illegible]

[illegible]

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE(BETA) PARAMETER= 1.[illegible]
LOWER LIMIT= 0.4244
UPPER LIMIT= 4.1319

SCALE PARAMETER= 1716.490[illegible]
LOWER LIMIT= 202.1257
UPPER LIMIT= 14576.7692

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | [illegible] | [illegible] |
| SHAPE | [illegible] | [illegible] |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | [illegible] | [illegible] | [illegible] |
| 5.0000 | [illegible] | [illegible] | [illegible] |
| 10.0000 | 313.7911 | 130.3368 | 755.4647 |
| 20.0000 | 553.0200 | 184.1287 | [illegible] |
| 50.0000 | 1301.5014 | 203.3149 | 8331.4[illegible] |
| 70.0000 | 1974.7725 | 200.8776 | [illegible] |
| 90.0000 | 3222.2530 | 194.[illegible]799 | [illegible] |
| 95.0000 | 3930.6185 | 191.1276 | [illegible] |
| 99.0000 | 5438.4487 | 185.[illegible] | [illegible] |
| 99.9000 | [illegible]356.6246 | 179.[illegible] | [illegible] |

L10

| LCL | MED | UCL |
|---|---|---|
| 130.3368 | 313.7911 | 755.4647 |

L50

| LCL | MED | UCL |
|---|---|---|
| 203.3149 | 1301.5014 | 8331.4[illegible] |

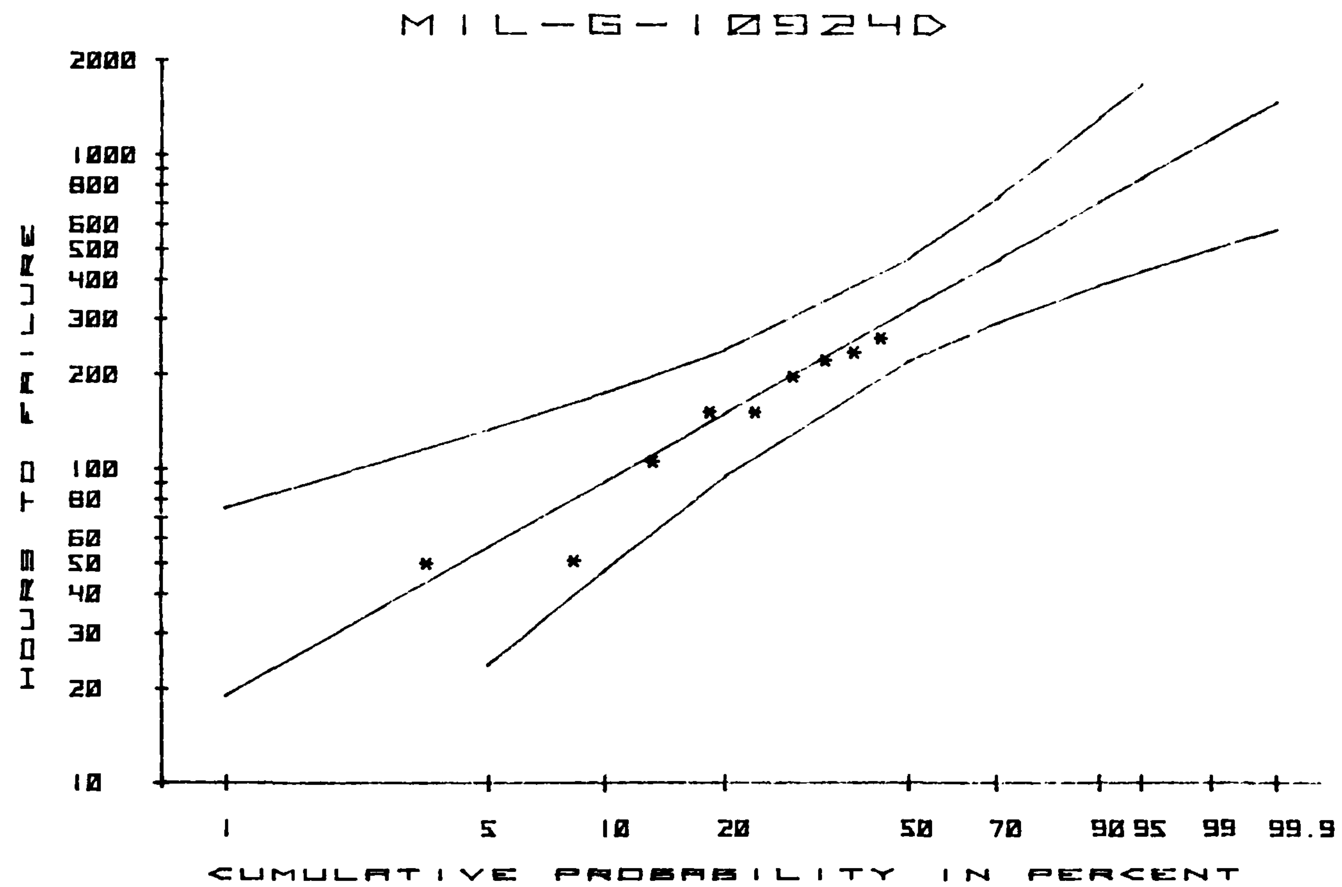



**Figure 9. Life of product F, MIL-G-10924D.**

TABLE [illegible] OF PRODUCT [illegible]

[illegible]

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE (BETA) PARAMETER= [illegible]
LOWER LIMIT= 0.9081
UPPER LIMIT= 2.4781

SCALE PARAMETER= 407.[illegible]
LOWER LIMIT= 267.0733
UPPER LIMIT= 622.9290

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 11024.3014 | -24.2637 |
| SHAPE | 24.2637 | 0.2095 |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 18.9996 | 4.8041 | 75.1415 |
| 5.0000 | 56.3161 | 23.7959 | 133.2798 |
| 10.0000 | 90.9977 | 47.4370 | 174.5595 |
| 20.0000 | 150.0675 | 94.2227 | 239.0111 |
| 50.0000 | 319.4665 | 219.1886 | 465.6212 |
| 70.0000 | 461.6102 | 292.0015 | [illegible] |
| 90.0000 | 711.2060 | 385.0408 | 1313.6633 |
| 95.0000 | 847.5822 | 426.6830 | 1683.6754 |
| 99.0000 | 1128.9341 | 501.3379 | 2542.1819 |
| 99.9000 | 1479.2952 | 580.8162 | 3767.6537 |

L10

| LCL | MED | UCL |
|---|---|---|
| 47.4370 | 90.9977 | 174.5595 |

L50

| LCL | MED | UCL |
|---|---|---|
| 219.1886 | [illegible] | [illegible] |

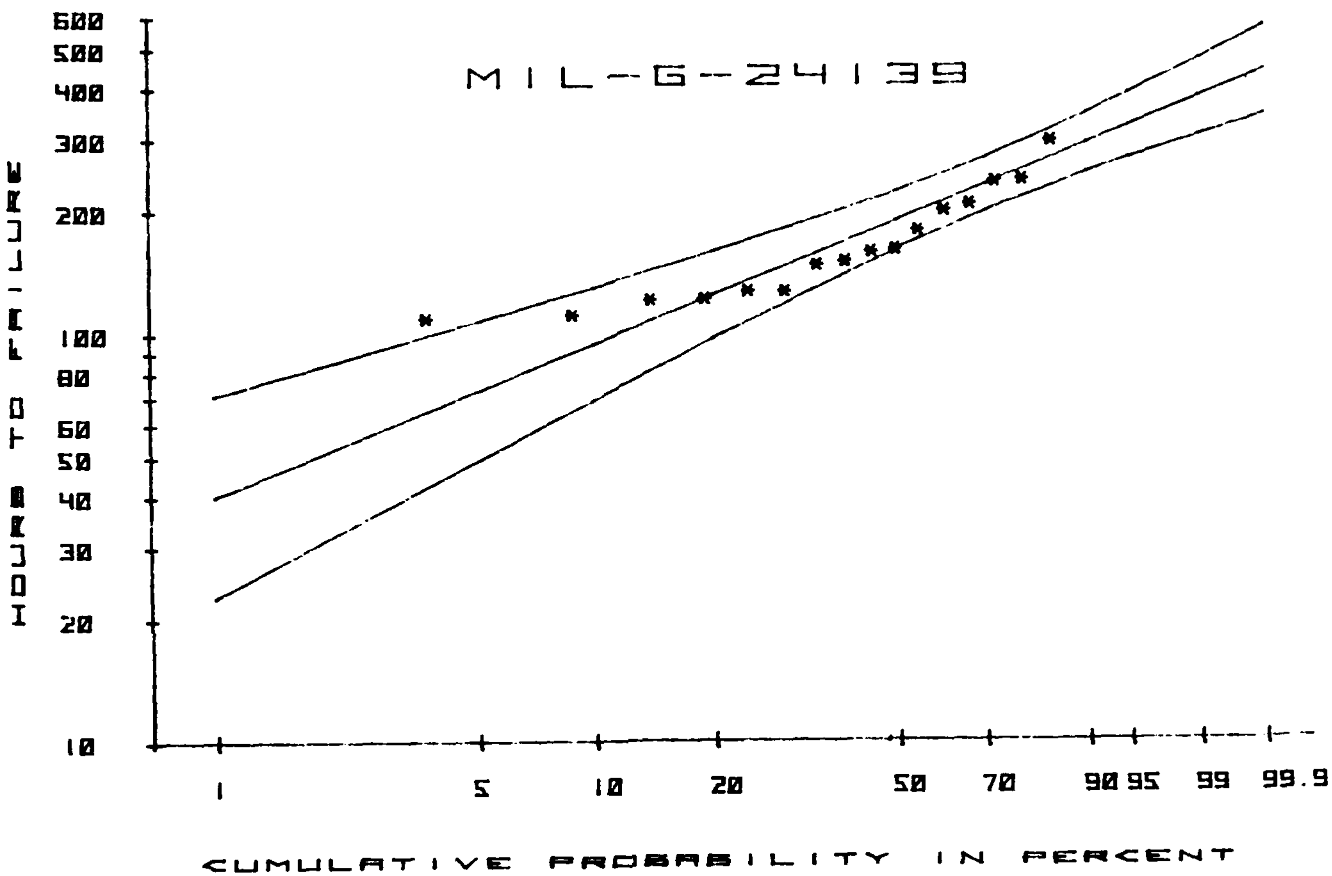



**Figure 10. Life of product G, MIL-G-24139.**

TABLE 10.LIFE OF PRODUCT G,MIL-G-24139

F(X)=1-EXP(-(X/A)↑B)

ESTIMATE AND TWO SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE(BETA) PARAMETER= 2.[illegible]
LOWER LIMIT= 2.0085
UPPER LIMIT= 3.7751

SCALE PARAMETER= 213.1877
LOWER LIMIT= 183.3530
UPPER LIMIT= 247.8772

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 381.7383 | 1.5370 |
| SHAPE | 1.5370 | 0.2790 |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 40.1075 | 22.6943 | 70.8818 |
| 5.0000 | 72.4940 | 48.9725 | 107.3131 |
| 10.0000 | 94.1529 | 68.5401 | 129.3370 |
| 20.0000 | 123.6492 | 96.7877 | 157.9656 |
| 50.0000 | 186.6189 | 158.6426 | 219.5289 |
| 70.0000 | 228.0549 | 196.4687 | 264.7191 |
| 90.0000 | 288.6065 | 244.4522 | 340.7360 |
| 95.0000 | 317.5493 | 264.8802 | 380.6911 |
| 99.0000 | 371.2183 | 299.9139 | 459.4754 |
| 99.9000 | 430.1099 | 335.4210 | 551.5293 |

L10

| LCL | MED | UCL |
|---|---|---|
| 68.5401 | 94.1529 | 129.3370 |

L50

| LCL | MED | UCL |
|---|---|---|
| 158.6426 | 186.6189 | 219.5289 |

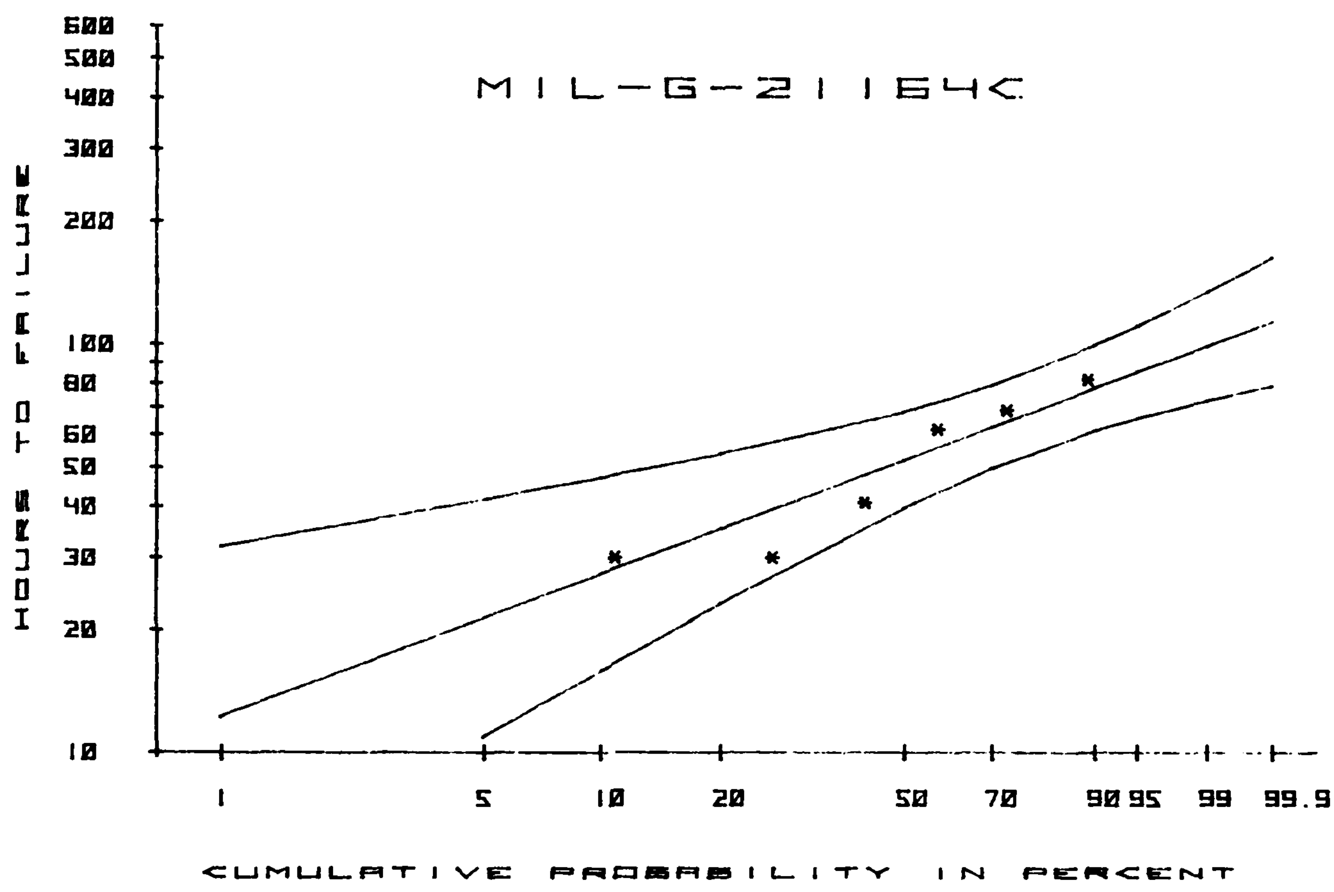



Figure 11. Life of product H, MIL-G-21164C.

TABLE 11. LIFE OF PRODUCT H, MIL-G-21164C

F(X)=1-EXP(-(X/A)↑B)

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE(BETA) PARAMETER= 2.9310
LOWER LIMIT= 1.7041
UPPER LIMIT= 5.0412

SCALE PARAMETER= 58.9283
LOWER LIMIT= 46.2644
UPPER LIMIT= 75.0587

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 25.1216 | 2.7162 |
| SHAPE | 2.7162 | 0.9336 |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 12.2663 | 4.7092 | 31.9508 |
| 5.0000 | 21.3908 | 10.9632 | 41.7364 |
| 10.0000 | 27.3454 | 15.8529 | 47.1693 |
| 20.0000 | 35.3245 | 23.1354 | 53.9355 |
| 50.0000 | 52.0017 | 39.6325 | 68.2312 |
| 70.0000 | 62.7810 | 49.7280 | 79.2604 |
| 90.0000 | 78.3256 | 61.5448 | 99.6817 |
| 95.0000 | 85.6832 | 66.0296 | 111.1867 |
| 99.0000 | 99.2220 | 73.0186 | 134.8287 |
| 99.9000 | 113.9426 | 79.4202 | 163.4711 |

L10

| LCL | MED | UCL |
|---|---|---|
| 15.8529 | 27.3454 | 47.1693 |

L50

| LCL | MED | UCL |
|---|---|---|
| 39.6325 | 52.0017 | 68.2312 |

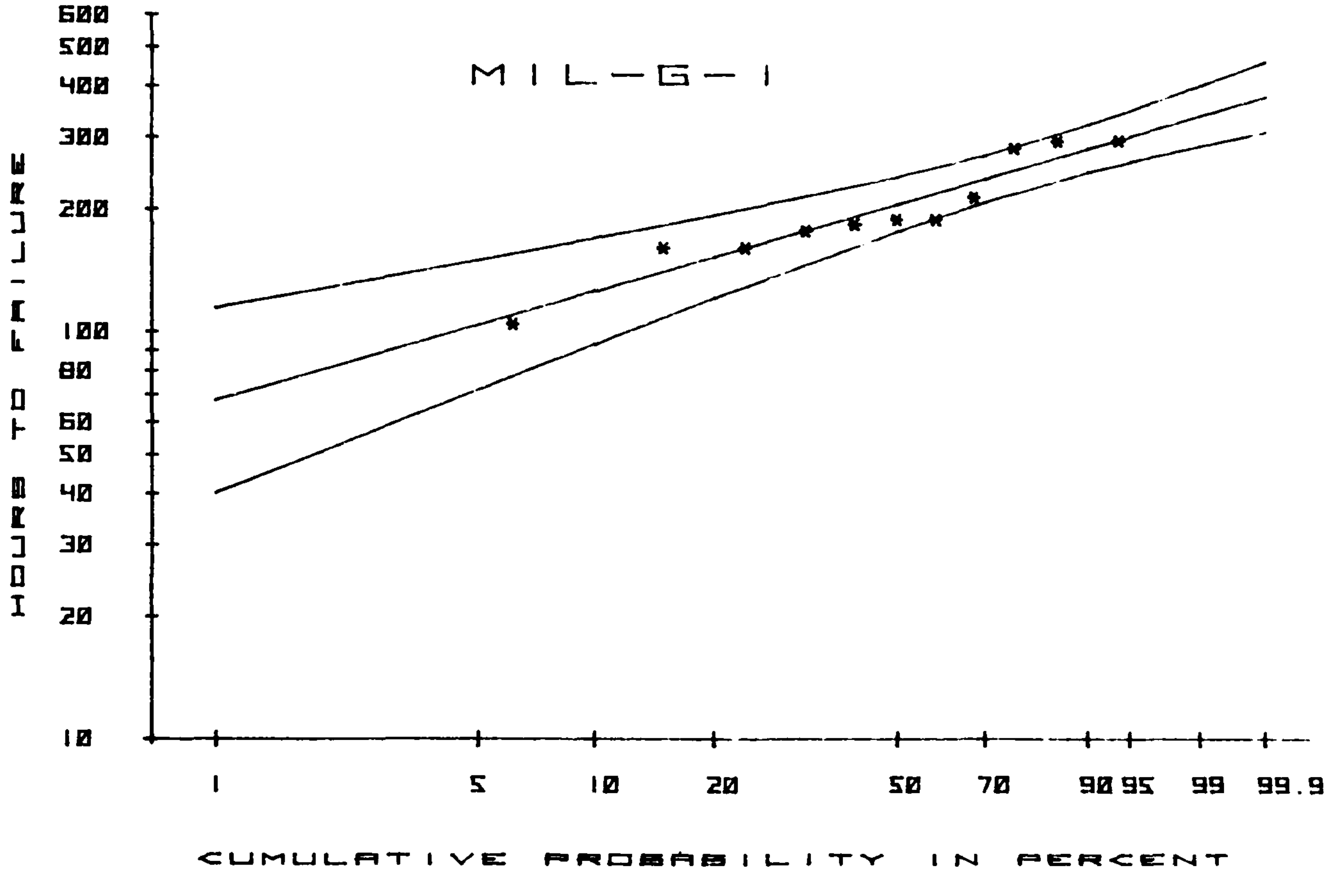



Figure 12. Life of product I, experimental formulation.

TABLE 12. LIFE OF PRODUCT 1, EXPERIMENTAL FORMULATION

F(X)=1-EXP(-(X/A)↑B)

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE(BETA) PARAMETER= 3.8265
LOWER LIMIT= 2.6095
UPPER LIMIT= 5.6111

SCALE PARAMETER= 225.1870
LOWER LIMIT= 196.3099
UPPER LIMIT= 258.3120

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 352.9357 | 5.4967 |
| SHAPE | 5.4967 | 0.7929 |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 67.6774 | 40.1696 | 114.0222 |
| 5.0000 | 103.6185 | 71.8634 | 149.4055 |
| 10.0000 | 125.0648 | 92.6786 | 168.7682 |
| 20.0000 | 152.1618 | 120.3827 | 192.3301 |
| 50.0000 | 204.6188 | 175.5459 | 238.5066 |
| 70.0000 | 236.3803 | 207.0871 | 269.8172 |
| 90.0000 | 280.0290 | 244.6248 | 320.5572 |
| 95.0000 | 299.9648 | 259.5148 | 346.7197 |
| 99.0000 | 335.6392 | 283.5894 | 397.2422 |
| 99.9000 | 373.1569 | 306.4586 | 454.3715 |

L10

| LCL | MED | UCL |
|---|---|---|
| 92.6786 | 125.0648 | 168.7682 |

L50

| LCL | MED | UCL |
|---|---|---|
| 175.5459 | 204.6188 | 238.5066 |

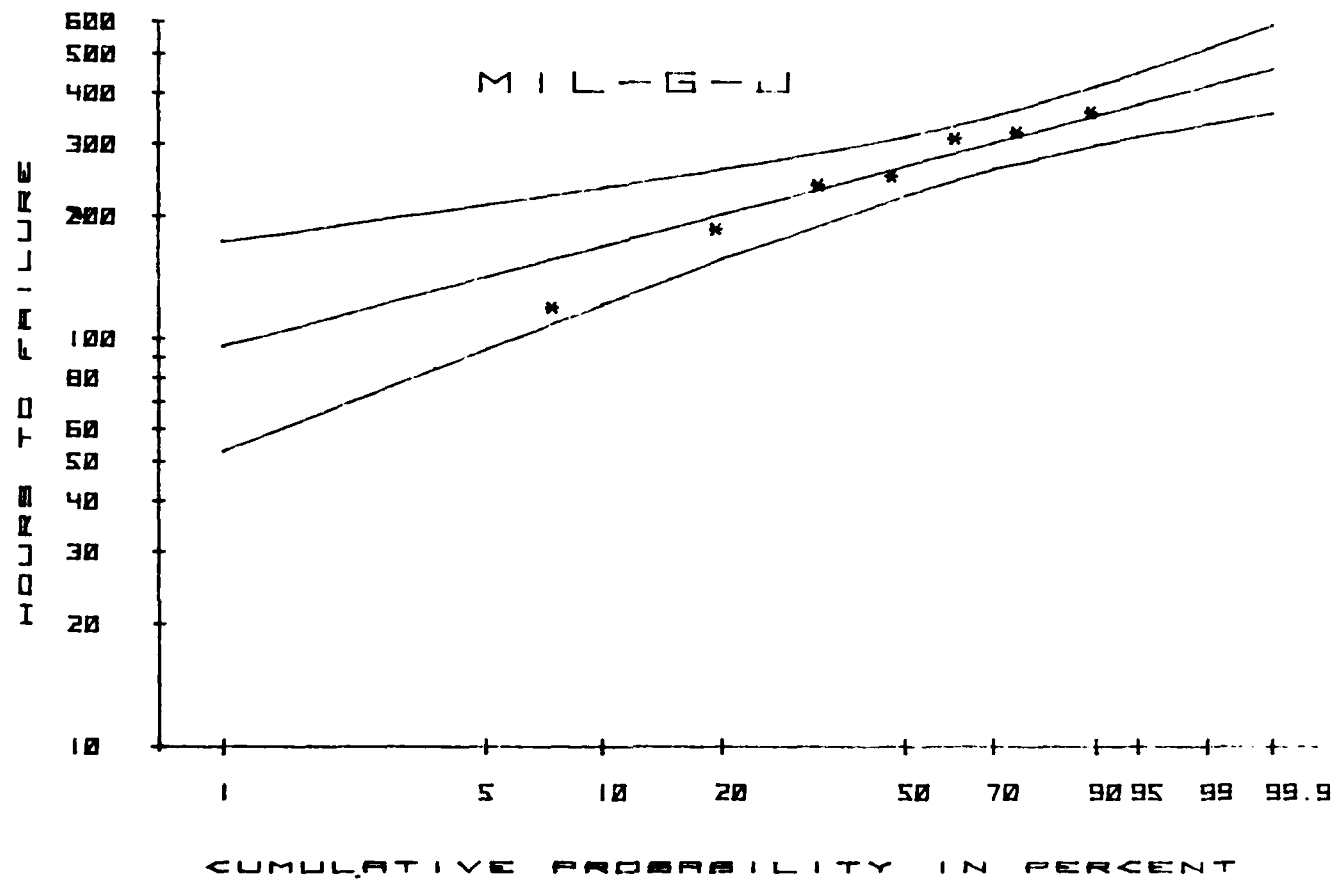



Figure 13. Life of product J, experimental formulation.

[illegible]

[illegible]

[illegible]
[illegible]

SHAPE PARAMETER= [illegible]
LOWER LIMIT= 2.5[illegible]
UPPER LIMIT= [illegible].8[illegible]

SCALE PARAMETER= [illegible]
LOWER LIMIT= 247.2[illegible]4[illegible]
UPPER LIMIT= 3[illegible]5.6258

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 707.4168 | 6.2403 |
| SHAPE | 6.2403 | 1.5018 |

ESTIMATES AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 95.7446 | 53.0269 | [illegible] |
| 5.0000 | 141.5088 | 94.1471 | 212.6965 |
| 10.0000 | 168.1565 | 120.9104 | 233.8643 |
| 20.0000 | 201.2933 | 156.1487 | 259.4896 |
| 50.0000 | 264.1270 | 223.8614 | 311.6352 |
| 70.0000 | 301.5002 | 259.7203 | 350.0009 |
| 90.0000 | 352.1949 | 298.7280 | 415.2314 |
| 95.0000 | 375.1252 | 313.3061 | 449.1419 |
| 99.0000 | 415.8493 | 336.1445 | 514.4533 |
| 99.9000 | 459.2924 | 357.1931 | 588.0067 |

T10

| LCL | MED | UCL |
|---|---|---|
| 120.9104 | 168.1565 | 233.8643 |

T50

| LCL | MED | UCL |
|---|---|---|
| 223.8614 | 264.1270 | 311.6352 |

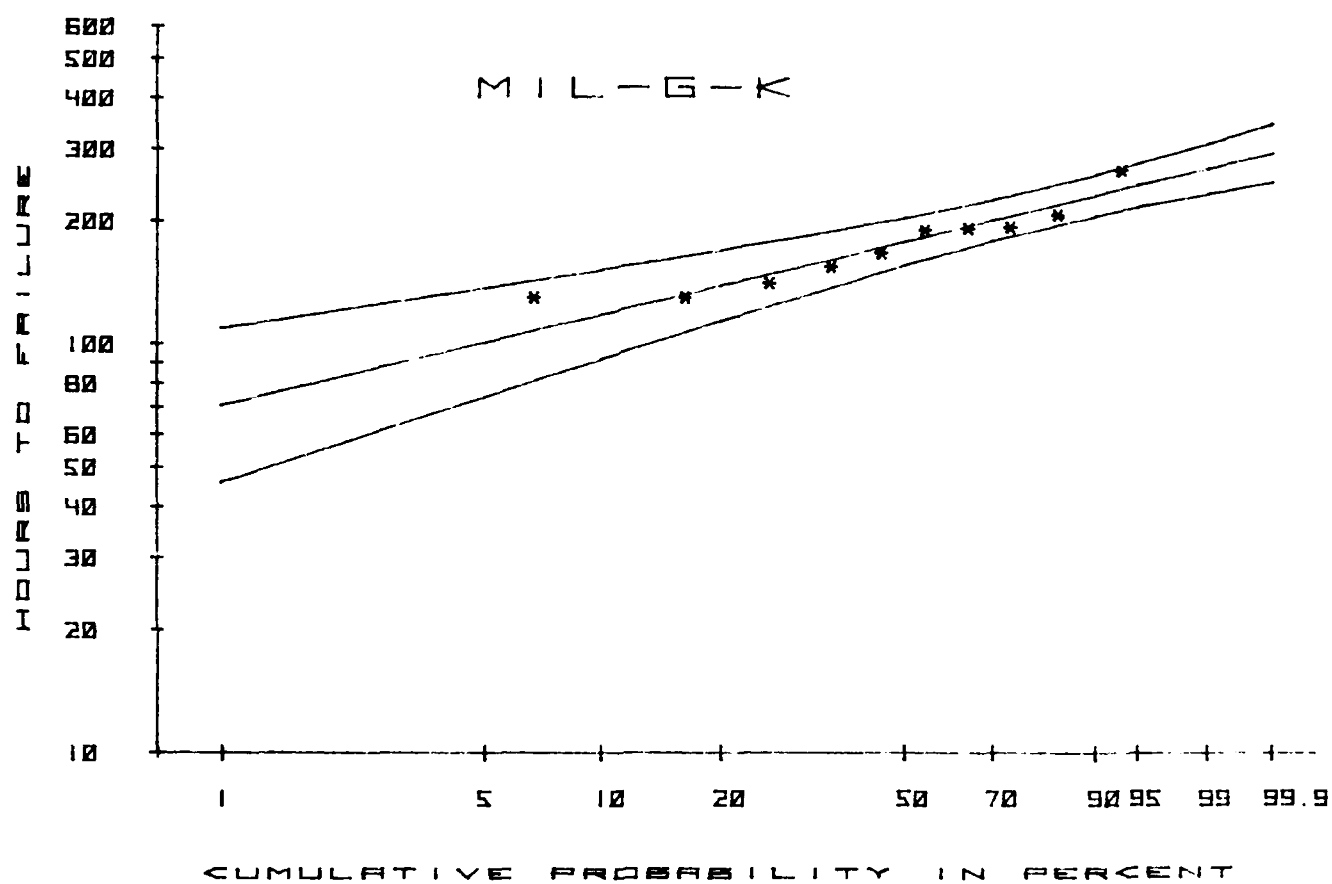



Figure 14. Life of product K, experimental formulation.

TABLE 14.LIFE OF PRODUCT K,EXPERIMENTAL FORMULATION

F(X)=1-EXP(-(X/A)^B)

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PARAMETERS

SHAPE(BETA) PARAMETER= 4.5940
LOWER LIMIT= 3.1499
UPPER LIMIT= 6.7001

SCALE PARAMETER= 193.0490
LOWER LIMIT= 171.1681
UPPER LIMIT= 217.7270

ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES

| | SCALE | SHAPE |
|---|---|---|
| SCALE | 199.3052 | 5.0155 |
| SHAPE | 5.0155 | 1.1107 |

ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS
FOR DISTRIBUTION PERCENTILES

| PERCENTAGE | PERCENTILE ESTIMATE | LOWER LIMIT | UPPER LIMIT |
|---|---|---|---|
| 1.0000 | 70.9237 | 45.9760 | 109.4084 |
| 5.0000 | 101.1298 | 74.4522 | 137.3666 |
| 10.0000 | 118.2847 | 91.9122 | 152.2242 |
| 20.0000 | 139.2741 | 114.1293 | 169.9588 |
| 50.0000 | 178.2457 | 155.9713 | 203.7011 |
| 70.0000 | 201.0091 | 178.9849 | 225.7435 |
| 90.0000 | 231.4798 | 205.9918 | 260.1214 |
| 95.0000 | 245.1267 | 216.6199 | 277.3849 |
| 99.0000 | 269.1782 | 233.6516 | 310.1065 |
| 99.9000 | 294.0158 | 249.6177 | 346.3107 |

L10

| LCL | MED | UCL |
|---|---|---|
| 91.9122 | 118.2847 | 152.2242 |

L50

| LCL | MED | UCL |
|---|---|---|
| 155.9713 | 178.2457 | 203.7011 |

Two different manufacturers supplied the greases A and B under the same Military Specification MIL-G-10924C. The $L_{10}$ life of these greases obtained was about 37 h and 31 h, respectively. Their average $L_{10}$ life value (34 h) was seven times less than the theoretical fatigue life of the bearings. The grease E (MIL-G-23549A/ASG, General Purpose) showed the best overall performance among the greases tested. Its $L_{10}$ life value was approximately nine times greater than the conventional GAA grease (MIL-G-10924C).

In the long-life grease program with some of the above greases, field tests are being conducted by this laboratory (Materials, Fuels, and Lubricants) utilizing military vehicles. After the field tests have been completed, a comparison will be made with the greases tested under laboratory environment.

Eventually, Phase II and Phase III of this project will be developed. As a result of these Phases, it is expected to be possible to determine the desirable $L_{10}$ life of greases in military vehicles. In future studies, an attempt will be made to apply the ML computer program also to hydraulic fluids, lubricants, and engine oils.

## APPENDIX A

## THE MAXIMUM LIKELIHOOD (ML) COMPUTER PROGRAM FOR THE TWO PARAMETER WEIBULL DISTRIBUTION

```
10 REM MAXIMUM LIKLIHOOD COMPUTER PROGRAM FOR WEIBULL DISTRIBUTION
20 FIXED 4
30 R=C=B6=0
40 D8=-9999.99
50 DIM S[100,2],X[100,2],Y[10,4],N[100,2],A$[20]
60 FOR K=1 TO 100
70 FOR J=1 TO 2
80 S[K,J]=0
90 X[K,J]=0
100 N[K,J]=0
110 NEXT J
120 NEXT K
130 FOR I=1 TO 10
140 FOR N=1 TO 4
150 Y[I,N]=0
160 NEXT N
170 NEXT I
180 FOR J=1 TO 100
190 DISP "ENTER DATA  X(J,1),X(J,2)";
200 INPUT X[J,1],X[J,2]
210 IF X[J,1]=0 THEN 260
220 S[J,1]=LOGX[J,1]
230 S[J,2]=X[J,2]
240 R=R+1
250 NEXT J
260 REM
270 FOR J=1 TO R-1
280 L=J
290 J1=J+1
300 FOR I=J1 TO R
310 IF S[L,1] <= S[I,1] THEN 330
320 L=I
330 NEXT I
340 T=S[L,1]
350 W3=S[L,2]
360 S[L,1]=S[J,1]
370 S[L,2]=S[J,2]
380 S[J,1]=T
390 S[J,2]=W3
400 NEXT J
410 FOR L=1 TO R
420 IF S[L,2]=2 THEN 490
430 N[L,1]=EXP(S[L,1])
440 N[L,2]=(L-0.3)/(R+0.4)
450 C=C+1
460 B6=B6+1
470 NEXT L
480 GOTO 560
490 FOR I=C+1 TO R
500 IF S[I,2]=2 THEN 550
510 N[I,1]=EXP(S[I,1])
520 B5=(R+1-B6)/(2+R-I)
530 B6=B6+B5
540 N[I,2]=(B6-0.3)/(R+0.4)
550 NEXT I
560 REM
```

```
570 DISP "ENTER A,B";
580 INPUT A,B
590 REM
600 C=E=F=F2=G=L=M=N=W1=W2=M1=M2=0
610 GOSUB 2420
620 H=F2-N
630 IF ABS(H-D8)<0.0001 THEN 710
640 PRINT H,D8,M1,M2,M3,M4,M5,Z1,Z2
650 Y=H
660 D8=Y
670 A=Z1
680 B=Z2
690 GOTO 600
700 REM
710 PRINT H,D8,M1,M2,M3,M4,M5,Z1,Z2
720 L1=EXP(Z1)
730 L2=1/Z2
740 REM
750 X1=M4/Y2
760 X2=M3/Y2
770 X3=(-1)*M5/Y2
780 PRINT X1,X2,X3,Y2
790 D1=(L1↑2)*X1
800 D2=(1/(Z2↑4))*X2
810 D3=-(1/(Z2↑2))*L1*X3
820 P1=Z1-1.645*(X1↑0.5)
830 P2=Z1+1.645*(X1↑0.5)
840 E1=EXP(1.645*(X2↑0.5)/Z2)
850 P3=Z2/E1
860 P4=Z2*E1
870 U1=EXP(P1)
880 U2=EXP(P2)
890 U3=1/P4
900 U4=1/P3
910 PRINT
920 PRINT
930 PRINT TAB17"ESTIMATES FOR THE CUMULATIVE WEIBULL DISTRIBUTION";
940 PRINT
950 PRINT
960 PRINT TAB28"F(X)=1-EXP(-(X/A)↑B)";
970 PRINT
980 PRINT
990 PRINT TAB17"ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS";
1000 PRINT
1010 PRINT TAB28,"FOR DISTRIBUTION PARAMETERS";
1020 PRINT
1030 PRINT
1040 PRINT "SHAPE(BETA) PARAMETER=";L2
1050 PRINT "LOWER LIMIT=";U3
1060 PRINT "UPPER LIMIT=";U4
1070 PRINT
1080 PRINT "SCALE PARAMETER=";L1
1090 PRINT "LOWER LIMIT=";U1
1100 PRINT "UPPER LIMIT=";U2
1110 PRINT
1120 PRINT TAB11"ESTIMATED COVARIANCE MATRIX OF PARAMETER ESTIMATES";
1130 PRINT
1140 PRINT TAB31"SCALE"TAB47"SHAPE";
1150 PRINT
1160 PRINT TAB19"SCALE"TAB29,D1,D3
1170 PRINT TAB19"SHAPE"TAB29,D3,D2
```

```
1180 PRINT
1190 REM
1200 FOR I=1 TO 10
1210 READ Y[I,1]
1220 DATA 1,5,10,20,50,70,90,95,99,99.9
1230 NEXT I
1240 FOR K=1 TO 10
1250 Q=LOG(-LOG(1-(Y[K,1]/100)))
1260 Q1=Z1+Q*Z2
1270 Q2=X1+(Q↑2)*X2+2*Q*X3
1280 Y[K,2]=EXP(Q1)
1290 Q3=Q1-1.645*(Q2↑0.5)
1300 Q4=Q1+1.645*(Q2↑0.5)
1310 Y[K,3]=EXP(Q3)
1320 Y[K,4]=EXP(Q4)
1330 NEXT K
1340 PRINT TAB17"ESTIMATE AND TWO-SIDED 90% CONFIDENCE INTERVALS";
1350 PRINT
1360 PRINT TAB28,"FOR DISTRIBUTION PERCENTILES";
1370 PRINT
1380 PRINT
1390 PRINT TAB14,"PERCENTAGE",TAB7,"PERCENTILE",TAB7,"LOWER LIMIT",TAB7;
1400 PRINT "UPPER LIMIT";
1410 PRINT
1420 PRINT TAB31"ESTIMATE";
1430 PRINT
1440 PRINT
1450 FOR J=1 TO 10
1460 PRINT TAB14,Y[J,1],Y[J,2],Y[J,3],Y[J,4]
1470 PRINT
1480 NEXT J
1490 PRINT
1500 PRINT "L10"
1510 PRINT
1520 PRINT TAB3"LCL"TAB18"MED"TAB33"UCL";
1530 PRINT
1540 PRINT Y[3,3],Y[3,2],Y[3,4]
1550 PRINT
1560 PRINT
1570 PRINT "L50"
1580 PRINT
1590 PRINT TAB3"LCL"TAB18"MED"TAB33"UCL";
1600 PRINT
1610 PRINT Y[5,3],Y[5,2],Y[5,4]
1620 IF Y[10,4] <= 600 THEN 2760
1630 SCALE -6,2.3,1.5,8
1640 YAXIS -5,15,2.3026,7.6009
1650 XAXIS 2.3026,20,-5,2.2
1660 FOR I=10 TO 100 STEP 10
1670 PLOT -5,LOG(I),1
1680 CPLOT -0.3,-0.3
1690 LABEL (*)"-"
1700 IF I=70 THEN 1750
1710 IF I=90 THEN 1750
1720 CPLOT -6,1
1730 STANDARD
1740 LABEL (*)I
1750 NEXT I
1760 IF Y[10,4] <= 600 THEN 2790
1770 FOR I=200 TO 1000 STEP 100
1780 PLOT -5,LOG(I),1
```

```
1790 CPLOT -0.3,-0.3
1800 LABEL (*)"-"
1810 IF I=700 THEN 1870
1820 IF I=900 THEN 1870
1830 CPLOT -6,1
1840 STANDARD
1850 LABEL (*)I
1860 IF I=1500 THEN 1950
1870 NEXT I
1880 Y8=2000
1890 PLOT -5,LOG(Y8),1
1900 CPLOT -0.3,-0.3
1910 LABEL (*)"-"
1920 CPLOT -6,1
1930 STANDARD
1940 LABEL (*)Y8
1950 FOR N=1 TO 10
1960 PLOT LOG(LOG(1/(1-(Y[N,1]/100)))),2.3026,1
1970 CPLOT -0.3,-0.3
1980 LABEL (*)"1"
1990 CPLOT -1,-1
2000 STANDARD
2010 LABEL (*)Y[N,1]
2020 NEXT N
2030 FOR I=1 TO R
2040 IF N[I,1]=0 THEN 2080
2050 PLOT LOG(LOG(1/(1-(N[I,2])))),LOG(N[I,1]),1
2060 CPLOT -0.3,-0.3
2070 LABEL (*)"*"
2080 NEXT I
2090 FOR K=1 TO 10
2100 IF Y[K,2]<10 THEN 2130
2110 IF Y[K,2]>2000 THEN 2130
2120 PLOT LOG(LOG(1/(1-(Y[K,1]/100)))),LOG(Y[K,2])
2130 NEXT K
2140 PEN
2150 FOR P=1 TO 10
2160 IF Y[P,3]<10 THEN 2180
2170 PLOT LOG(LOG(1/(1-(Y[P,1]/100)))),LOG(Y[P,3])
2180 NEXT P
2190 PEN
2200 FOR H=1 TO 10
2210 IF Y[H,4]>2000 THEN 2230
2220 PLOT LOG(LOG(1/(1-(Y[H,1]/100)))),LOG(Y[H,4])
2230 NEXT H
2240 DISP "ENTER A$";
2250 INPUT A$
2260 PEN
2270 IF Y[10,4] <= 600 THEN 2740
2280 PLOT -3.5,7.8,1
2290 LABEL (*,2,2.7,0,6.5/2.3)
2300 LABEL (*)A$
2310 PEN
2320 PLOT -5.8,3,1
2330 LABEL (*,2,1,1.5708,2.3/6.5)
2340 LABEL (*)"HOURS TO FAILURE"
2350 PEN
2360 PLOT -4.7,1.6,1
2370 LABEL (*,1,2,0,6.5/2.3)
2380 LABEL (*)"CUMULATIVE PROBABILITY IN PERCENT"
2390 PEN
```

```
2400 GOTO 2880
2410 REM
2420 FOR K=1 TO R
2430 A1=(S[K,1]-A)/B
2440 A2=EXP(A1)
2450 F=F+A2
2460 A4=A1↑2*A2
2470 G=G+A4
2480 A5=A1*A2
2490 M=M+A5
2500 IF S[K,2]=2 THEN 2560
2510 L=L+A1
2520 A9=-LOG(B)-A2+A1
2530 F2=F2+A9
2540 C=C+1
2550 GOTO 2570
2560 N=N+A2
2570 NEXT K
2580 PRINT C,R,F,G
2590 REM
2600 M1=1/B*(F-C)
2610 M2=1/B*(M-L-C)
2620 P=B↑2
2630 M3=(1/P)*F
2640 M4=1/P*(2*M2+C+G)
2650 M5=1/P*(B*M1+M)
2660 Z3=M3*M4
2670 Z4=M5*M5
2680 Y2=Z3-Z4
2690 Z1=A-(M4*M1+(-M5*M2))/Y2
2700 Z2=B-((-M5*M1)+M3*M2)/Y2
2710 RETURN
2720 N=0
2730 GOTO 2590
2740 PLOT -3,6,1
2750 GOTO 2290
2760 SCALE -6,2.3,1.5,6.5
2770 YAXIS -5,15,2.3026,6.3969
2780 GOTO 1650
2790 FOR I=200 TO 600 STEP 100
2800 PLOT -5,LOG(I),1
2810 CPLOT -0.3,-0.3
2820 LABEL (*)"-"
2830 CPLOT -6,1
2840 STANDARD
2850 LABEL (*)I
2860 IF I=600 THEN 1950
2870 NEXT I
2880 END
```

# APPENDIX B

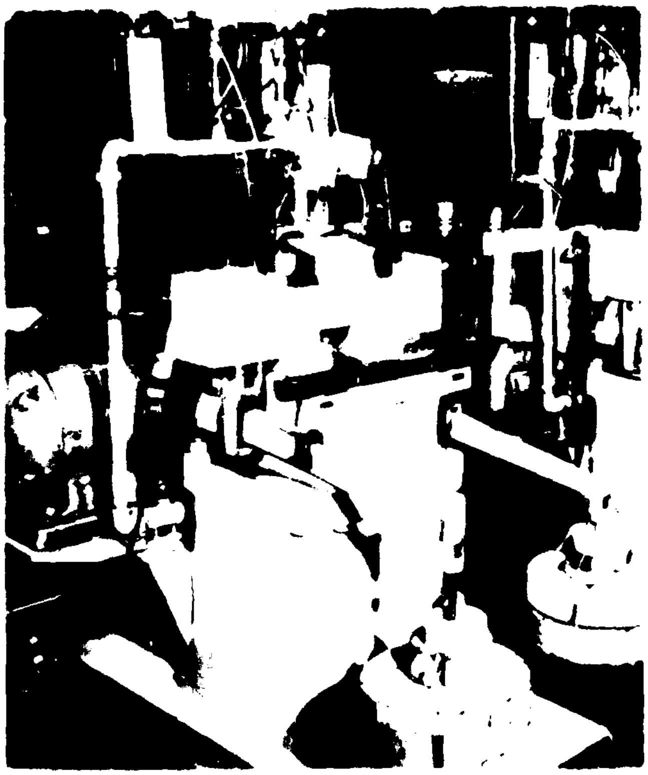
## SKF ENDURANCE TEST METHOD (MODIFIED INDUSTRIAL TEST METHOD)

**B-1. Endurance of Bearing-Grease System.** The tests were conducted on a basic SKF Industries, Inc., R-2 Endurance Test Machine which was modified to accept a simulated front wheel hub assembly. A detailed description of the design and operation of this test machine, the test procedures, and the conditions under which the tests were performed in order to evaluate the lubrication characteristics of each grease are presented in the following paragraphs.

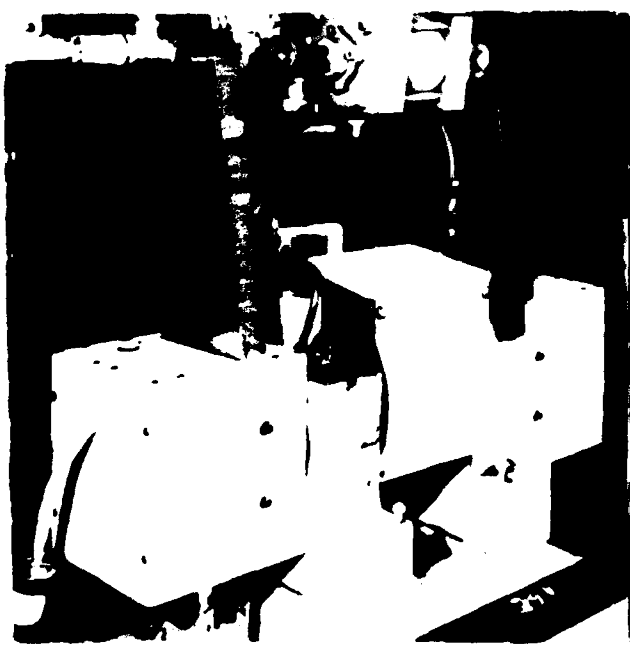
**a. Endurance Test Machine.** The basic configuration of the test machine consists of a central belt-driven horizontal arbor which is supported by two cylindrical roller bearings. Photographic views of the machine are shown in Figure B-1. A hub containing a pair of tapered roller-bearing test specimens is mounted on each end of the arbor, as shown in the assembly drawing of Figure B-2. A constant radial force is applied to each hub assembly by a dead weight through a lever and linkage arrangement. A thrust force is applied inward by an air cylinder mounted between the hubs at a prescribed distance from the bearing axis. This offset simulates a cornering force on the hub assembly as would be produced at the tire periphery when a car turns. The thrust force is applied cyclically every 5 min for 1-1/2 min duration.

**(1) Elevated Temperature Tests.** For the elevated temperature tests, a Chromalox 500-W ring heater, fastened to the side of the load arm, surrounds the hub as shown in Figure B-2. It provides additional heat over and above that caused by internal bearing friction to bring the bearing temperature to the required level of operation. Power to the dual element heater is controlled manually through a Powerstat. One element of the heater is on constantly and supplies that amount of heat needed to bring the operating temperature of the test bearings to within 10 K to 15 K of the specified level. The second element, powered through the same Powerstat, is thermostatically controlled to maintain the total temperature at the prescribed operating level. An insulated housing (Figure B-2) surrounding each hub assembly maintains the temperature at an even level and prevents rapid thermal fluctuations.

**(2) Room Ambient Temperature Test.** In order to assess the effect of operational temperature on grease performance, the lubrication characteristics of two greases, one of which had been run previously under elevated temperature conditions (1), was also determined at 304 K. Exploratory tests showed that this could be accomplished by dissipating the heat generated by the test bearings through fan cooling. Except for the elimination of the heater and insulated housing, all other test conditions were the same.



**(a) Overall view**



**(b) Enclosed test head**

**(c) Test hub and heater**

**Figure B-1. Photographs of front wheel bearing test machine.**

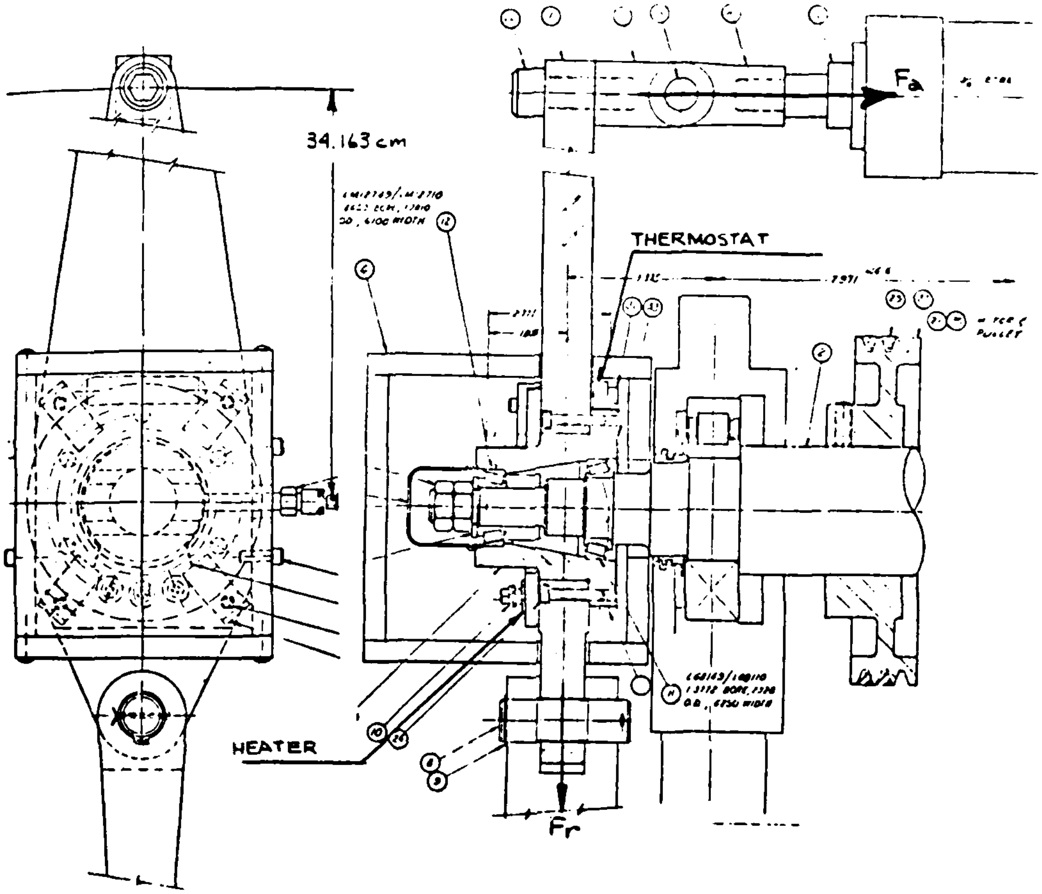



**Figure B-2. Schematic of hub assembly front wheel bearing grease test machine.**

**(3) Operational Parameters.** The operating temperature of each bearing was measured by an iron-constantan thermocouple in contact with the outer ring (cup) outer diameter surface. An automated test floor control system containing a Data General Nova 800 mini computer system, used as a central processing unit (CPU), monitored and recorded the operational temperature of each test bearing. The control system is programmed to provide alarms and/or to stop a machine whenever the bearing operating temperature exceeds present temperature limits. In addition, a special subroutine known as the Temperature Rate of Increase Monitor (TRIM) was used to detect an impending failure as the result of a lubrication deficiency. The TRIM, which was developed as a means of anticipating the ultimate failure of the grease pack contained in a bearing, automatically terminates a test when the rate of temperature rise is greater than or equal to a preset limit for a time period sufficient to produce a preset absolute temperature increase. In this study, the TRIM values were 1 K/min rise with a maximum increase of 12 K. Concurrently, the maximum temperature of operation was set at 423 K.

**b. Test Procedures.** The following test conditions and the procedures employed were common to all tests run and are based upon an industrial method used to evaluate the endurance of commercial wheel bearings. In this test procedure, a hub assembly is subjected to a radial load equivalent to 150 percent of the vehicle curb weight. In addition, a thrust load or cornering load equal to 30 percent of the radial load is applied intermittently at a distance from the center of the bearing axis which is equivalent to the tire radius.

On the basis of the weight of a medium size sedan, the bearings were subjected a constant radial load of 8.34 kN (1875 ft-lb). In addition, a thrust load of 2.49 kN (560 ft-lb) was applied at a distance of 34.2 cm (13.45 in.) from the horizontal centerline of the bearing axis every 5 min for a duration of 1-1/2 min or 30 percent of the time.

The bearings were run at an inner ring speed of 800 r/min which is approximately equivalent to a vehicle speed of 105 k/h (65 mi/h). Each pair of test bearings was lubricated with the test grease in the following manner: The bearings were packed full and 40 g of grease was distributed in the hub cavity between the bearings. Except where noted, the bearings were run to a preset time-up life of 300 h which is approximately equivalent to 32,000 km (20,000 m) or until failure, whichever occurred first. The onset of failure was defined as:

(1) A distinct increase in the normal operating vibration level as detected by a viberswitch mounted on the test system.

(2) An increase in the noise level.

(3) A gradual heat imbalance reducing the power input required to heat the environment to 50 percent of its original value.

(4) A sudden heat imbalance resulting in an increase in bearing temperature at an excessive rate as determined by the limits established in the TRIM included in the test floor control computer system.

(5) An increase in temperature above a preset limit of 423 K.

An indication of failure by any of these modes automatically terminated the test run. Three test rigs were employed in order to complete this study in a reasonable time interval.

The following describes the basic differences in the two types of tests run in this study:

**(1) Type I—Elevated Temperature Endurance Test.** To establish the endurance life characteristics of a grease, a group of 20 pairs of bearings was run under the above test conditions at an operating temperature of 394 K ± 4 K (121° C) with the aid of heaters for a period of 300 h or failure.

**(2) Type II—Room Ambient Temperature Endurance Test.** The effect of operational temperature on grease endurance life was based on the results of a group of 20 pairs of bearings run with the specified test grease in a room temperature environment but without the use of heaters and the transite insulation enclosure. The test bearing operational temperature was maintained at 304 K ± 4 K (30° C) by means of fan cooling. One fan centrally located between the test bearings was sufficient to dissipate the heat generated by the bearings.

**c. Test Bearing Description.** The endurance characteristics of each grease was determined using bearings of the following configuration:

| Bearing No. | Basic Size mm: Inner Diameter | Outer Diameter | Width | Location on Test Arbor |
|---|---|---|---|---|
| LM12749/LM12710 | 21.979 | 45.974 | 15.494 | Outboard |
| L68149/L68110 | 34.981 | 59.974 | 15.875 | Inboard |

These bearings were part of a statistically similar sample group produced according to SKF Industries, Inc., manufacturing standards and tolerances for material and geometry.

**B-2. Method of Calculation to Determine the $L_{10}$ Life of the Test Bearing System.** The $L_{10}$ life of the two bearing systems employed as calculated herein is based upon formulas and methodology concepts currently in use by the bearing industry.

The test conditions employed were:

a. Test Bearing Specimens: Outboard—LM12749/LM12710 = Brg. No. 1; Inboard—L68149/L68110 = Brg. No. 2

b. Applied Radial Load—8.34 kN (1875 lb): Applied at a distance of 45,847 mm (1.805 in.) from the outboard bearing presure center.

c. Thrust Load—2.49 kN (560 lb): Applied 30 percent of the time at a distance of 34.163 cm (13.45 in.) from the horizontal axis of the bearing centerline.

d. Speed—800 r/min.

e. Distance between the outboard bearing and inboard bearing pressure centers is 70.536 mm (2.777 in.).

f. Life Formula: $L_{10} = \left(\frac{C}{P}\right)^{10/3}$.

g. Life of System (two bearings): $\frac{1}{L^e} = \frac{1}{(L_1^e)} + \frac{1}{(L_2^e)}$ where e = 1.125.

h. The $L_{10}$ life of system is 234 h from the above equations.

## APPENDIX C

### LIST OF ACRONYMS

AFBMA-ASA: Antrifiction Bearing Manufacturers Association (AFBMA) and American Standards Association (ASA).

$B_{10}$Life: Median bias corrected 90% reliable.

$L_{10}$ Life: Median bias corrected 90% reliable life.

$L_{50}$ Life: Median bias corrected 50% reliable life.

ML: Maximum likelihood.

MED: Median.

LCL: Lower end of 90% confidence interval.

UCL: Upper end of 90% confidence interval.

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